ELECTRIC TRANSMISSION OF ENERGY.

THE

SPECIALISTS'

SERIES.

ELECTRIC TRANSMISSION OF ENERGY,

AND ITS

TRANSFORMATION, SUBDIVISION, AND DISTRIBUTION.

A PRACTICAL HANDBOOK.

BY

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PREFACE.

With the discovery of the electro-dynamic principle made independently by Varley, Siemens, and Wheatstone in 1866, the era of heavy electrical engineering may be said to have commenced. But its progress was at first very slow. It was fully twelve years later until, thanks to the International Exhibition in Paris, the Gramme dynamo became extensively known; and the greatest development in dynamo machines has only taken place within the last few years. The machines which could be seen at the Electrical Exhibition in Paris in 1881 were all more or less of the character of scientific apparatus. They could hardly be called substantial mechanical appliances; and English engineers were quick in perceiving that to make dynamos of real practical value considerable improvements of a purely mechanical nature were necessary. Since then a good deal of honest and valuable work has been done in this direction, notwithstanding the disastrous speculations of Electric Light Companies some years ago, and we possess now dynamos which in point of efficiency can hardly be further improved. But there is still room for improvement as

regards their weight, which in many cases appears to be excessive. It is a fact difficult to explain that electro-motors have hitherto been so much neglected, whereas dynamos have received all the attention. There are a number of firms in this country whose principal business is to manufacture dynamos, but there is no firm of importance occupied exclusively with the manufacture of motors. Consequently, when motors were required for transmission of energy—as, for instance, in electric railways—the only means of doing the work was by adapting a dynamo to act as a motor, and thus get a rough-and-ready arrangement, by no means the best which could be devised. This state of things is gradually mending, as some dynamo makers have begun to devote attention to the manufacture of motors. In doing so they are forced to abandon, for the most part, their special "systems," because the conditions to be fulfilled by dynamos and motors are different. This, however, is rather an advantage than otherwise. Some years ago the first requirement of an electric company who aspired to get the confidence of the public, was to have a special system. This magic word was the key to commercial success—for a time. Now we have grown wiser. We know that practical success does not so much depend on the system, as on the men who plan and carry out electrical work; and the less of a special system and the more of general good engineering there is, the better. Many of the general public, and even many of our professional brethren, regard

electrical engineering, especially as applied to the transmission of energy, as something uncertain, mysterious, and as yet in the experimental state. It has been the aim of the author to dispel this impression by presenting the scientific part of the subject in as simple a form as possible, and by giving descriptions of work actually carried out. He has endeavoured in this way to place before the reader an unbiassed report on the present state of electric transmission of energy.

May, 1886.

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ELECTRIC TRANSMISSION OF ENERGY.

INTRODUCTORY.

THE transmission of energy and its transformation is the fundamental problem of mechanical engineering. No piece of mechanism yet devised is able to create energy, but all mechanism has for its object the transmission and transformation for useful purposes, of energy already existing in nature in a more or less inconvenient form. The more perfect our mechanical appliances, the better are they fitted to direct the forces of nature to do useful work; and in this sense the electric transmission of energy must be regarded simply as an improvement on purely mechanical methods already existing. But it is something more. It not only improves mechanical methods, but extends the field for their application, inasmuch as it can, in many instances, reach nearer to the sources of power than any mechanical means.

The most important natural sources of power are fuel, wind, and water. As regards the first-named, electric transmission can hardly be considered of any great importance for the purpose of reaching the source of power, for fuel, especially in its most useful form of coal, is so

easily portable, that in most cases it is more convenient to carry the fuel to the place where the energy is required than to transform it into energy where found and transport the energy to the place of application. It has been suggested to erect large generating stations for electricity close to the pit's mouth, and work the dynamos by steam-power obtained from the small coal which is not worth being carried by rail. The current generated could then be sent along wires to neighbouring towns, and thus the energy contained even in the refuse of our coal-fields could be utilized. As yet this suggestion has not been carried into practice, except on a very limited scale, namely, in providing motive power for underground railways in coal mines.

The other two great natural forces, wind and water, especially the latter, offer a larger field for the application of electricity. Water-power is only portable in a very limited sense. The great cost of channels, and the difficulty of providing elevated reservoirs close to those places where the power would be of greatest use, compel us in most cases to establish our factories close to natural waterfalls; in other words, we cannot carry water-power to the work, but must take the work to where the water-power is. Where that is impossible or inconvenient, the power cannot be directly utilized. It is in these cases that electric transmission of power is of greatest value, inasmuch as it enables us to get at many sources of energy which would otherwise be wasted. The amount of energy contained in waterfalls all over the world is enormous. To cite only one or two cases. According to Herr Japing, the hourly weight of water falling in the Niagara is one hundred million tons, representing about sixteen million horse-power, and the total production of

coal in the world would just about suffice to pump the water back again. M. Chretien, a French engineer, has in a paper read at the Paris Electrical Exhibition in 1881, given the total water-power in France as seventeen million horse-power, and has suggested, that if by electric transmission only a part of this vast amount of energy were made available for useful purposes, an enormous economy in the consumption of fuel in France would be effected, and, at the same time, the hydraulic works necessary would also have the beneficial result of preventing, or at least mitigating droughts and inundations. This suggestion has already borne fruit, although only on a small scale. Near Bienne, in Switzerland, there is a waterfall representing an energy of several thousand horse-power. A small portion of this power is utilized by a turbine, which works a generating dynamo. The current is conveyed by an overhead line, consisting of a pair of copper wires (270 mils diameter) to Bienne, a distance of about a mile, where it works two electro-motors ; one in a mill where silver is rolled, and where the power required is very variable ; the other in a watch factory where, on account of the delicate nature of the work, an absolutely constant speed is required. The installation has now been at work with perfect success for over two years.

Another instance of electric transmission in connection with water power is the electric railway at Portrush, in Ireland, where the energy of a waterfall is by means of a turbine and dynamo converted into electrical energy, which is conveyed to the line and along the rails into the motor of the car. There it is reconverted into mechanical energy and utilized in propelling the car. Examples of this class might be multiplied, but these two will suffice to show that a practical beginning has already been

made in the application of electricity for the purpose of reaching some sources of energy which would otherwise be lost. If progress in this direction has not been as fast as might be desired, the reason lies in this, that installations of this kind are necessarily of some magnitude, and cannot be undertaken as mere experiments. If a small installation of electric lighting were to turn out a failure in any particular case, the loss to the contractor would not be so very serious. The dynamo, the wire, and the lamps have all their fixed market value, and if they have to be removed from one installation, they can be utilized in another. Not so with the transmission of energy from some hitherto inaccessible source. The dynamo and the motor have to be built specially for each particular case, and the probability that they can be used elsewhere is small. The line and supports are expensive items, which have only value in that particular locality where they have been erected, and the works necessary for transforming the crude energy of nature so as to be applied for driving the generating dynamo, have also only a local value. In such cases the installation must be a complete success, or else most of the plant and work is a dead loss; and it is but natural that capitalists shrink from rushing into enterprises as long as there is the least taint of an experimental nature about them.

Another reason which has, in England at least, operated to delay the electric transmission of energy from natural and inaccessible sources to more convenient places, is that in this country coal is cheap and water-power scarce. In France the case is different, and accordingly we find that the first experiments on a large scale have been undertaken there. Although it is quite incorrect to say, as is frequently stated in French papers, that M. Marcel Deprez has in-

vented the electric transmission of energy, or has even invented any special system by which the electric transmission of energy is made practicable, it must be admitted that he has had the courage of his opinion, and has been the first to demonstrate that energy can be transmitted electrically over long distances. All scientists have long been agreed on the necessity of employing for long distance transmission currents of high electromotive force, but M. Marcel Deprez was the first to carry this into practice.

Broadly speaking, there are two purposes for which the electric transmission of energy is of great value. The one comprises all cases where, as has been shown above, hitherto inaccessible sources of natural energy are by its means rendered accessible, and the other comprises all those cases where the source of energy itself is accessible, but where it is desired to distribute it to a number of independent small working centres. In the first case we have to transmit a large amount of energy, so to speak, in one lump from the distant source to the place of operation ; and, in the second case, we have to split up the energy of a source close at hand into a number of small fragments, and distribute them within a limited area to do useful work. In this case electric transmission of energy comes into competition with the more mechanical means of belts, shafts, wire-ropes, and pneumatic or hydraulic tubes, and the question whether one or the other of these systems is preferable, depends on the amount of energy transmitted, and the distance over which it is transmitted, as well as on many local circumstances. Electricity has the great advantage of being extremely portable, and capable of having its direction and intensity changed with greatest ease. No mechanical

force can be detected in the conductor carrying the electrical energy such as appears during purely mechanical transmission with shafting, belts, wire-ropes, or in pipes conveying steam, water, or air. The conductor is clean, cold, does not move, and altogether appears inert. It can be bent, moved, or shifted in any manner while transmitting many horse-power. It might be brought round sharp corners, and, having little weight, it can be fixed with greater ease than any mechanical connection. It is thus possible to bring the energy into rooms and places awkwardly situated for mechanical transmission, and there is no noise, smell, dirt, or heat during the transit, nothing to burst or give way. The power is, moreover, under perfect control, and its application exceedingly elastic. The same circuit which may be tapped to give many horse-power can, at the same time, and as conveniently be used to work a sewing-machine, or other small domestic implement, and the power consumed at the generating dynamo is always in proportion to the power obtained from all the motors, so that there is no waste of energy if some of the motors are standing still or are working with less than their full load. In addition to these advantages, electrical distribution of energy has also the merit of being exceedingly economical. The commercial efficiency of dynamos and electro-motors seldom falls below 80 per cent., and is in many cases as high as 90 per cent., so that even if we make a liberal allowance for loss of energy in the conducting wires, 60 per cent. of the power of the prime-mover at the generating station can be recovered from the motors distributed over a limited area. For instance, a steam-engine of 100 horse-power, driving a generating dynamo in the centre of a two-mile circuit, could deliver an

aggregate of sixty horse-power in as many separate points within that circuit. Apart from all considerations of nuisance and cost of attendance in the case of sixty separate small steam-engines placed throughout the district, which might be used instead of the sixty electromotors, it is evident that we can generate one hundred horse-power in one single engine at a far less cost of fuel than could be done in small engines, and although the double conversion necessitated by electrical distribution of energy entails some loss, there is still a large margin in the general economy of the system.

In some cases it is found convenient to transmit the energy from the generating dynamo, not directly to the motors, but to interpose between the two a set of accumulators or secondary batteries. This is in reality an extension of the system, and has the double advantage of providing motive power even at those times when the generating dynamo is standing still, and also of giving to the motor a certain amount of portability. Electric transmission of power is thus actually carried beyond the limits of a fixed conductor, or is even effected without the aid of a conductor at all. As a case in point, may be cited the propulsion of street tramcars by means of secondary batteries. Here we have a charging station at some place near the line containing some prime mover and dynamos, the current from which is sent by a pair of cables to the secondary batteries in the car which are to be charged. This is the first stage in the electric transmission of energy. When the cells are fully charged, the cables are detached, and the car is ready to start, and during its journey the second stage of the transmission, viz., that of the energy in the cells into the motor, takes place. By the employment of secondary batteries, we

have thus carried the operation beyond the limits of the cables. If the charging station is so situated that cars can enter it, the process of charging can be accelerated by making each set of cells detachable from the car, and charging them whilst the car, furnished with a duplicate set, is on the line. As each car comes in, its set of exhausted cells is replaced by a set newly charged, and can go out again within a few minutes. In this case the actual transmission of energy between the dynamo and the cells, which are placed in close proximity, is only over the space of a few yards ; yet this energy may, later on, be utilized over a very long line.

A similar system is in use for the propulsion of small boats by electricity. It can be most conveniently applied in the case of launches belonging to vessels which are fitted with the electric light; for the same dynamo which works the incandescent lamps at night can be used to charge, or keep charged, the accumulators in the launch during the day-time, so that the latter may at a moment's notice be lowered into the sea, provided with a sufficient store of energy for some hours' run. When the launch is stowed away on deck, its accumulators can also be used for lighting the vessel, if a mishap occurs to the dynamo, or if it be necessary to stop the machinery for some other reason.

Examples of this kind might be multiplied to any extent, but sufficient has been said to show that in the present state of electrical industry the electric transmission of energy is a question of great practical interest. Its application is not only confined to the transmission of power, pure and simple, between two distant points, as commonly understood, but it enters more or less into every application of electricity.

CHAPTER I.

General Principles—Lines of Force—Relations between Mechanical and Electrical Energy—Absolute Measurements—Ideal Motor and Transmission of Energy—Practical Units.

A PROPER understanding of the principle of the conservation of energy, which exists throughout the whole of nature, must necessarily form the basis of all scientific investigation of mechanical or electrical problems, and of most of the improvements we might attempt to introduce in existing machinery and apparatus. In many cases, the fact that the original amount of energy remains unchanged, whilst the form in which it becomes manifest undergoes many alterations, is easily understood. For instance, if a locomotive engine draws a train behind it on a railway, we are at no loss to explain how the energy of fluid pressure of steam in the boiler is transformed into that of a steady pull overcoming the resistance of the train at a speed of so many miles per hour, and including all the so-called waste caused by deformation, friction, abrasion, and heating of the bodies through which the energy flows. The means by which, in this case, energy is transformed are, for the most part, purely mechanical, and sufficiently familiar to our imagination to allow us to form a mental picture of the different processes taking place. Even the transformation of heat into energy of fluid pressure, although we are not able to represent it by a

mechanical model, has, through long familiarity with heat engines in one form or another, become comprehensible to us. With electrical energy, and with that of chemical action, this is not so. We can form no kind of mental picture of the process taking place in a voltaic cell where the energy of chemical action is transformed into that of an electric current, nor can we say what are the connecting links by the aid of which this current, after passing through hundreds of miles of wire, is made to impart mechanical energy to the armature of an electro-magnet, and thereby produce telegraphic signals. There is no mechanical connection between the sending key and the lever of the Morse instrument by which energy could be transmitted in the form of a pull, as is the case in our example of the coupling between a locomotive and its train, and yet energy is unmistakably transmitted. If we neglect waste, that is energy transformed in a way not immediately useful for the purpose in view, we find that the amount of electrical energy received at the distant station is proportional to the amount of chemical energy used up; and if we take the waste also into account, we shall find that the energy it represents, added to that received in the form of an electric current at the distant station, is again proportional to the amount of chemical energy developed in the voltaic cell. If we know the nature of the chemical process going on in the cell, we can always calculate, by the aid of electro-chemical equivalents, what total amount of electrical energy can be obtained from a given weight of materials.

Similarly there exists a definite and constant proportion between electrical and mechanical energy. The relation between the two is somewhat complicated by the development of heat, which, indeed, is inseparable from

electric phenomena, but if we make due allowance for the energy wasted in heat, we shall find that a given amount of electrical energy will always produce the same amount of mechanical energy, irrespective of the time required, or the exact manner of transformation. Although we cannot say what are the connecting links between electric current and mechanical force, experiment shows that certain definite relations exist, and we can, on the basis of experimental facts, conceive a mental picture or model by the aid of which these relations are represented in a familiar form. Such a mental picture is the conception of magnetic lines of force, first introduced by Faraday. In adopting this method of rendering electro-mechanical phenomena tangible to our senses, we make no assumption whatever about the reality of the lines of force. Whether they actually exist is a matter of total indifference; but since all the experiments we can make are compatible with that conception, and since it enables us not only to explain experimental facts, but also to bring them within the region of actual measurement and calculation, it is convenient to make the theory of magnetic lines of force the basis of electro-mechanical investigations.

If a sheet of paper be laid over a straight steel magnet having opposite poles at its ends, and sprinkled with iron filings, it will be found that these arrange themselves in curves, which we take to be the magnetic lines of force,[1] Fig. 1. Each of these lines form a closed curve

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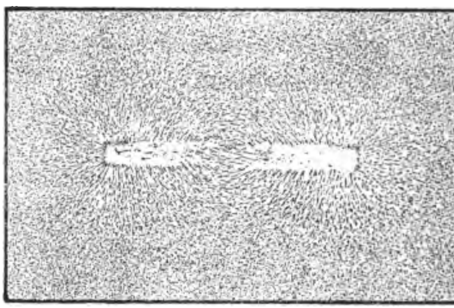
[1] A very convenient way of fixing these curves is by the aid of a sheet of glass, the surface of which has been coated with a thin layer of paraffin. The glass is laid over the magnet, then sprinkled, and carefully lifted off so as not to disturb the filings. It is then gently heated, when the paraffin melts, and upon cooling again the iron filings are fixed to the glass by the coating of paraffin. The glass plate may then be handled as if it were a drawing, and the curves can be reproduced by photography. The drawing in the text has been obtained in this manner.

issuing from a point at one end of the magnet, and entering at a corresponding point at the other end. Some of the curves extend far out into space, beyond the surface of the paper, and as far as they are visible, they appear as open lines growing fainter the farther we go from the poles. They must, nevertheless, be considered to be closed lines, only so faint that we cannot trace them throughout their whole length. If the poles of our magnet were two mathematical points, all the curves would pass through those points, but since we

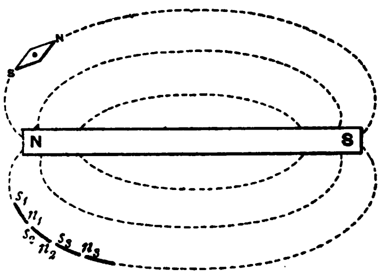
Fig. 1.



have to deal with a physical magnet, the poles of which are surfaces of some extension, the lines issue from all over these surfaces. To investigate the magnetic properties of these lines we can use a long thin magnetic needle (a magnetized knitting-needle answers very well) suspended vertically by a long thread, so that the lower end of the needle is within a short distance of the paper, and free to move all over it. We shall then find that the lower end of the needle will be repelled by one pole of the magnet and attracted by the other, and in following the combined action of these forces, it will move along that particular

line of force upon which it was set on to the paper in the first instance, but it will never move across the lines. We conclude from this experiment that the lines of force are paths along which a free magnet pole is urged under the influence of the magnet. A free magnet pole of opposite sign would travel along the same lines, but in opposite direction, and, if of the same strength, it will be urged along with an equal force. If, instead of a long vertical needle, we take a very short one suspended horizontally in its centre close to the surface of the paper, the two

Fig. 2.

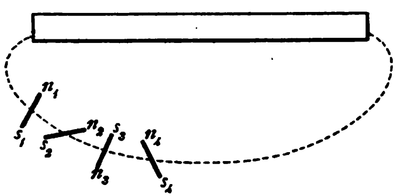


opposite forces will tend to set the needle so as to form a tangent to the line of force passing through its centre, and as then the two forces are equal and opposite, no bodily shifting of the needle can take place. But on whatever point of any of the curves we set the needle, it will always swivel into such a position that its magnetic axis, that is a straight line joining its two poles, becomes a tangent to the curve. (Fig. 2.) It should here be remarked that unless the needle is very short in comparison to the magnet it will, when placed near one of the poles, be drawn right up to it, because in this case there would be a sensible difference in the distance of either of its poles from

that magnet pole, and consequently the opposing forces would no longer be in equilibrium. But if the needle is very short, say only the length of a particle of iron filing, this inequality between the attracting and repelling force will at a short distance from the magnet pole become omissible, and then the particle of iron filing will only set itself into the direction of the line of force in that place, but not move bodily along it. We may thus regard each particle of iron filing which has been sprinkled over the paper as a very short magnetic needle, and each line of force as a chain of such needles linked together by their poles of opposite sign—n_1 s_1—n_2 s_2—n_3 s_3—and so on, as shown in Fig. 2. Imagine now that the particles in one such chain, whilst under the influence of the magnet, could by some process be suddenly hardened into steel, or that we had taken steel filings in the first instance, and then remove the magnet. We would then have a succession of little magnets, whose poles of opposite sign touch, and therefore eliminate each other, with exception of the first and last particle of the chain. Here we would have a free N pole at one end, and a free S pole at the other end, these being a finite distance apart, and therefore able to exert magnetic action on other pieces of iron placed into their neighbourhood. But let each particle be turned round its centre (without however, shifting it, bodily) so as to break contact with its neighbour, and we shall have a disjointed line of very small magnets, Fig. 3, none of which is able to exert any magnetic attraction or repulsion at a distance, because on account of the proximity of the two opposite poles in each particle, their distances from any external point to be acted on would be sensibly equal, and consequently the opposite forces would be in equilibrium. By turning each particle so as

to thoroughly break contact with its neighbour, we have completely destroyed the magnetic action of our chain at a distance. If we had turned only a few of the particles, or if we had turned all through a very small angle, so as not to completely interrupt their magnetic continuity, the magnetism of the chain as a whole would have been weakened but not destroyed completely. We can restore our magnetic chain again by turning each particle back into its original position, and if this process should be too laborious to be performed by hand, we can accomplish it in an instant by replacing our magnet under the paper,

Fig. 3.



when its line of force corresponding to the chain of particles, will pass through it again and swivel each into a tangential position, whereby poles of opposite sign are again brought into contact, thus eliminating each other, with the exception of the two free poles at the ends of the chain.

According to Professor Hughes' theory of magnetism,[1] what has here been described for a chain of iron filings lying on the sheet of paper, actually takes place within the body of any piece of iron or steel whilst being

[1] Proceedings Royal Society, May 10, 1883; also a paper on "The Cause of Evident Magnetism in Iron, Steel, and other Magnetic Metals," read before the Society of Telegraph Engineers and Electricians, and reported in their Journal, vol. xii., No. 49.

magnetized. According to this theory, each molecule of iron or steel is a complete magnet; it is provided at one end with a definite quantity of magnetic matter of one sign, and at the other end with precisely the same quantity of magnetic matter of the opposite sign, and these magnetic charges are an inseparable attribute of matter like its gravity or chemical or thermal properties, and they can neither be increased nor diminished. In an unmagnetized bar of steel these molecular magnets are supposed to form a disjointed chain, their magnetic axes pointing in all possible directions, and therefore, as was the case in our chain of iron filings after we had rotated them, incapable of magnetic action at a distance. But if, by some means, it were possible to turn all the molecules so as to point one way, without, however, displacing them bodily, we would obtain a number of parallel magnetic chains showing free magnetism at their ends only, and therefore capable of exerting magnetic attraction and repulsion at a distance; in other words, our bar of steel would become a magnet. It will be seen that according to this theory the molecules composing a bar of magnetizable steel must be capable of rotation around their centres, and the more easily and completely they can be rotated, the greater is the degree of magnetization obtained. Since we cannot take hold of each molecule and rotate it mechanically, we must adopt the other method, viz., that of sending lines of force through the bar to perform that work, as we did with the chain of iron filings. This can be done either by the aid of another magnet, or by an electric current. The setting of molecules into continuous chains will be the more complete, the less resistance or internal friction they offer to rotation, and the more powerful are the lines of force which

are caused to pass through the bar of steel. In very soft steel, or in soft iron, the molecules rotate freely, and can be set almost completely into continuous chains, but the harder the steel the smaller is the angle through which each molecule can be rotated, and the more magnetizing force is required for this purpose. In such cases the magnetic chains are more or less discontinuous, and the magnetism appearing externally is weaker. On the other hand, the molecules once rotated into position of magnetic continuity are not so easily disturbed again, and thus the harder the steel the more permanent is its magnetization. In soft iron the molecules will lose their magnetic continuity as easily as it was acquired, and the slightest mechanical strain or vibration is sufficient to destroy the greater part of the previous magnetization. To illustrate this we may take a glass tube filled loosely with iron filings, which can be magnetized by drawing the pole of a magnet along it. We shall then see that the particles of filing which previously were lying in all possible directions, have now become more or less parallel to the tube, and the whole appears more like a solid piece of iron of very fibrous texture. The tube has now become a magnet, and if it be carefully handled so as not to disturb the arrangement of the particles, it can be used as if it were a solid steel magnet, and all the usual phenomena of attraction and repulsion at a distance can be obtained. But on tapping or shaking the tube the particles relapse into their former confused position, and all traces of external magnetism of our tube vanish. From this short outline of Professor Hughes' theory it will be seen that the only way in which we can act upon the molecules in the interior of a bar of iron or steel is by sending lines of force through it. The greater the number of lines, or the

more powerful the individual lines which we can force through the bar—or, in other words, the greater the magnetizing power—the greater will be the number of molecules which are thereby arranged into more or less complete magnetic chains, and if the metal is hard enough these chains in their turn become the seat and origin of lines of force, and can then be used to magnetize other bars. It will also be clear that after a bar has been magnetized, the space surrounding it becomes filled with lines of force which emanate from it. Strictly speaking, each magnet is surrounded by lines extending into infinite space, but practically they can only be traced throughout the space immediately surrounding the magnet, and this space is called the "*magnetic field.*" Since magnetic lines are not a reality, but only a convenient conception, we can adopt any simple way of expressing their magnitude, or, to speak more correctly, the intensity of the magnetic field at any given point. We can either assume that the lines are of different strength, and that the mechanical force with which a given free magnet pole is urged along any one particular line is dependent on the strength of that line, which may be different from that of any other line belonging to the same field; or we can assume that all the lines are of the same strength, but that the number of lines passing through unit space of the field is different at different points of it. According to this assumption, the intensity of the field in any given spot, and the mechanical force exerted on a free magnet pole, is proportional to the number of *unit lines* passing through unit space at that particular spot. This is the more convenient way of estimating the magnitude of the mechanical forces produced by the magnetic field, but it must not be considered to be a representation geometrically true, and if

we try to consider it so, the want of reality in our conception of lines of force becomes at once apparent. This will be seen from the following consideration. If, as we assume, a mechanical force can only be exerted by lines actually passing through the magnet pole, it will be evident that in case the pole be a mathematical point, only one line can pass through it and exert mechanical force on it. This force would therefore be quite independent of the density of lines around the pole. If the pole, although of the same strength, had finite dimensions, more lines would actually pass through it, and more mechanical force would be exerted. Experiment, however, shows that this is not the case, and that within reasonable limits the mechanical force is independent of the extent of the pole, and only depends on its free magnetism. From this we conclude that a strictly geometrical representation of the density of lines in a magnetic field, in the same manner as we might represent the density of trees in a forest, would be incorrect. We cannot pretend to solve the problem of finding a geometrical representation for our conception of the intensity of the magnetic field, and we must be content to use the term in its conventional sense, without having any clear idea of how it could be represented by a mechanical model. Yet this is no reason why we should abandon such an extremely convenient method of representing magnetic action at a distance. Nobody has as yet succeeded in explaining the action of gravitation, or has been able to represent it by a mechanical model. Nevertheless we find no difficulty in using the conventional terms of acceleration, mass, and weight of bodies in our calculations. We know that the weight of a body equals the product of its mass and the acceleration due to gravity. If we put strength of pole for

mass and intensity of field for acceleration due to gravity, we find the analogue to weigh in the mechanical force with which a free magnet pole is acted on when placed in a magnetic field.

From what has been said above, it will be evident that we must define *magnetic field of unit intensity* as that in which a free magnet pole of unit strength is acted on with unit force. To define a magnet pole of unit strength we must have recourse to the well-known expression for the mechanical attraction or repulsion existing between two poles placed at a certain distance apart. The law has been established experimentally by Coulomb,[1] with the aid of his torsion balance, and verified by Gauss,[2] who used for the purpose a large fixed magnet, and a smaller suspended magnetic needle. It is as follows. If M and m denote the strength of the two poles, and if they are placed at a distance, r, from each other, the mechanical force (attraction or repulsion according to whether the poles are of dissimilar or similar sign) acting between them is $\frac{M\,m}{r^2}$. If both poles are equal and of the strength m, we have $\frac{m^2}{r^2}$, and if their distance be unity, the force acting between them will equal the square of the free magnetism of one pole. The force will be unity if the free magnetism is unity. We find, therefore, the definition for *unit pole to be a pole of such strength that when placed at unit distance from an equal pole, the two will act upon each other with unit force.* It remains to define unit force and unit distance. This might be done on any convenient basis of the measurements of mass, length, and

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[1] Wüllner, "Experimentalphysik," iv., § 5.
[2] Wiedemann, "Elektricität," iii., p. 116, *ante.*

time. In electrical calculations it is customary to use for this purpose

The Gram as the unit of mass.

The Centimeter as the unit of length.

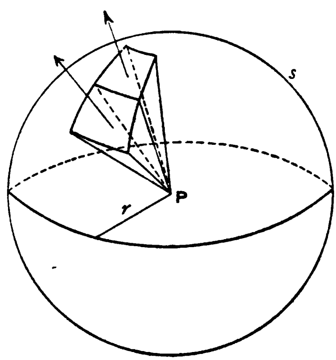
The Second as the unit of time.

On these units is based what is known as the *Absolute System of Electro-Magnetic Measurements.* Taking these units as the basis for our calculations, we can find all other units of measurement, because they are all connected in some way with the fundamental units of mass, length, and time. We find thus that the unit of velocity is one centimeter per second, that of acceleration is an increase of velocity of one centimeter per second, and since mechanical forces are measured by the product of mass and acceleration, we define the unit of mechanical force, the *Dyne,* as that force which applied to a mass of one gram, during one second, will give it a velocity of (or accelerate its velocity by) one centimeter per second. The mechanical energy represented by the force of one dyne acting through a distance of one centimeter is the unit of energy, and is called the *Erg.* Having accepted these fundamental and derived units, we can now proceed to establish units for the lines of force, and for the intensity of the magnetic field. We call a *unit line of force* one of such strength that if a unit pole be placed on it, it shall be urged along it with the force of one dyne. A *unit magnetic field* would be one in which a unit pole would be acted on with the force of one dyne. If we find experimentally that an equal force is exerted in all points of a certain portion of the field (as is the case with the magnetic field of the Earth within certain limits), we say that this particular portion of the field is of uniform magnetic intensity, and we consider all the lines of force to be

straight, parallel, and equidistant. A *uniform magnetic field of unit intensity* is therefore one in which every square centimeter of transverse section is traversed at right angles by one unit line. We can now determine the number of unit lines which emanate from a free unit pole. Before doing so, a few words of explanation regarding this conception of a free magnet pole are necessary. It has been shown above that magnets are produced by the adjusting of their molecules into continuous chains; and that, therefore, equal quantities of magnetic matter of opposite signs are produced at the poles of the magnet. Experiment shows that it is physically impossible to produce a magnet with one pole only, and that therefore no such thing as a free magnetic pole can be found in nature. But we can get an approximation to the free pole by making the magnet very long in comparison to the strength of its poles. In this way the magnetic influence of each pole will be sensibly felt through a distance considerably smaller than the length of the magnet, and when investigating the magnetic properties of the space immediately surrounding one pole we can neglect the disturbing influence of the other pole. In this case the lines of force emanating from the pole under consideration will be straight radii, shooting out from the pole all around into space. Let, in Fig. 4, P be the pole, and S a sphere described around it as centre, then this sphere will be pierced by the lines of force, in points which are all equidistant from the pole. Let r be that distance, and M the strength of the pole, we find the mechanical attraction exercised upon a unit pole of opposite sign placed at any point on the surface of the sphere, by the expression $\frac{M}{r^2}$. If, now, a second sphere be described around P, with a

radius larger than r by only an infinitesimal amount, we shall have a spherical shell of infinitely small thickness, within which the intensity of the field is uniform. Into whatever point between the two surfaces of the shell we may place our unit pole, we find that it is attracted with the same force towards P, and from this we conclude that the density of lines all over the spherical surface must be uniform. Since in a uniform field the force exerted upon unit pole in the direction of the lines is equal to their

Fig. 4.



density (or number of lines per square centimeter of transverse section), we conclude that through each square centimeter of surface on the sphere, there pass $\frac{M}{r^2}$ unit lines. Now the total surface of a sphere of radius r, is $4\,\pi\,r^2$, and consequently the total number of lines emanating from the pole of the strength M is

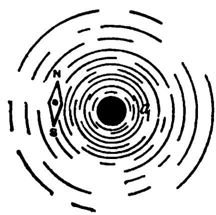
$$4\,\pi\,r^2 \times \frac{M}{r^2} = 4\,\pi\,M.$$

If the pole P, instead of having the strength M, were a

unit pole, the total number of lines would evidently be 4π, and thus we find a second definition for *unit pole* as a pole of such strength that 4π unit lines of force emanate from it. This definition is evidently identical with the following: *Unit pole produces unit intensity of field at unit distance.*

Up to the present we have only dealt with magnets and the mechanical forces exerted by them. It will now be necessary to investigate the relations between an electric current and the mechanical force it can exert when

Fig. 5.

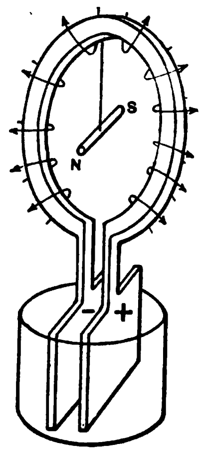


brought into a magnetic field. Experimental facts form now, as before, the basis of our investigation. Let, in Fig. 5, *a* be the cross-section of a wire passing vertically through the surface of the paper, and assume that a current is flowing down the wire. If we sprinkle iron filings on to the paper near the wire, we find that they arrange themselves in concentric circles around it, and if we shift the paper into other places along the wire, we find the same result. From this experiment we conclude that the wire throughout its whole length is surrounded by circular lines of force, or as it is sometimes called, by a magnetic whirl. If we suspend a long thin magnet parallel to the wire, so that its lower end is free to move along the surface of the paper, it will have a tendency to

rotate round the wire, but continuous rotation cannot be obtained, because the upper end of the magnet has a tendency to circle round the wire in an opposite direction. If a short magnetic needle, suspended in its centre, is placed horizontally on the paper, it will set itself tangentially to the lines of force, and therefore at right angles to the wire. Each circle of iron filings must be considered as a chain of small magnets closed in itself, and if we were to lay a ring of steel around the wire on the paper, it would become a continuous magnet. Upon removing the ring it would not show any external magnetization, because all along, its molecules are in contact with their opposite poles, but if we interrupt this continuity by cutting the ring open in one place, the ends severed will show opposite polarity when the ring is straightened out. If, instead of a complete ring, we had placed only a segment of a ring or a straight piece of steel at right angles to the wire, it would upon removal at once show magnetic properties. We see from these experiments that it is possible to magnetize a piece of steel by passing an electric current in its neighbourhood at right angles to it. All the experiments detailed above will succeed equally well with a bent wire, and if we employ a coil of wire with a piece of steel inserted at right angles to the plane of the coil, its magnetization will be considerably greater than where only one straight wire is used. The annexed sketch, Fig. 6, will give a clear idea of the lines of force surrounding a circular coil in which a current flows. The zinc and copper plate of a Daniell cell are joined by a stout square wire bent into the form of a circle, as shown, and since all the lines pass around the wire in the same sense it follows that the whole interior space of the circle is filled by a bundle of lines

piercing the plane of the wire at a right angle. A free magnet pole would therefore be drawn through the hoop in one sense or the other, according to the sign of the pole and the direction of the current. If a small magnetic needle be suspended in the centre, it will set itself at right angles to the plane of the circle and the direction in which its N pole is urged, is given by the following rule due to Ampère: *Imagine a person swimming with the*

Fig. 6.

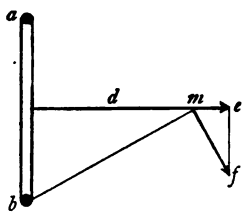


current and looking towards the needle, then its N pole will be urged towards the left. If, instead of a magnetic needle, we place a non-magnetic piece of steel into the same position it will become magnetized, N at its left and S at its right end. It will be evident that if we approach the N pole of a magnet to the circle from the front, the side turned towards the observer in the figure, it will be repelled, and if we approach a S pole it will be attracted. The opposite takes place on the back. The

same would happen if instead of the circular wire traversed by a current, we had a very short magnet of equal diameter. To put the magnet into the same condition as the wire its length would have to be equal to the thickness of the wire, and it would thus become a flat disc, one side of which we assume to be covered with N magnetic matter, and the other side with an equal amount of S magnetic matter. By properly choosing the amount of magnetism distributed over the discs, we can obtain a magnet which in its action at a distance is absolutely equivalent to the circular current, and such a magnet is called the *equivalent magnetic shell.* The action which a physical magnet or a magnetic shell equivalent to a closed current can exert at a distance is most conveniently expressed by the *magnetic moment,* that is the product of strength of poles with their distance. A magnet one centimeter long having unit poles has unit moment. Experiment shows that the magnetic moment of a plane closed circuit is equal to the product of area enclosed by the current and strength of the current, and we can therefore define unit current as *that current which flowing in a plane circuit is equivalent to a magnetic shell the moment of which is numerically equal to the area of the circuit.* Let in Fig. 7, *a b* represent the cross-section through a circular conductor of radius, *r*, traversed by a current, *c*, and *m*, a magnet pole placed at a distance, *d*, from the centre of the coil, then it is found experimentally that each element of the conductor exerts a force on the magnet pole which is numerically equal to the product of strength of current by length of element, by strength of pole divided by the square of the distance ; and the direction of which is at right angles to the plane passing through the element and through the magnet pole. The

force due to the element, $d\,l$, situate at b, is therefore $m\,f$, and its amount is $d\,F = \frac{c.\,dl.\,m.}{d^2 + r^2}$ The horizontal component of this force is evidently $d\,H = d\,F \frac{r}{\sqrt{d^2 + r^2}}$ and since the same holds good for any element along the circle, we find the total force by integration between the limits o and $2\,\pi\,r$ . . . . $H = c.\,m.\,\frac{2\,\pi\,r^2}{(d^2 + r^2)^{\frac{3}{2}}}$.

Fig. 7.



If the magnet pole lies in the centre of the coil, $d = o$, and the force is evidently $H = \frac{c.\,m.\,2\,\pi}{r}$.

This equation provides another definition for unit current. It will be seen that if m, r and c are equal to unity, H is equal to $2\,\pi$, and we may define unit current as *that current which, flowing in a wire forming a circle of unit radius, acts on a unit pole placed at the centre with a force of* $2\,\pi$ *dynes.*

If a magnet be inserted into a coil of wire which is connected to a delicate galvanometer, a current will be observed to flow through it for a short time, and if the magnet be withdrawn from the coil, a momentary current in the reverse direction is created. Now since it is impossible that a current should flow without there being

an electromotive force in the circuit, we conclude that the act of thrusting a magnet into the coil, or suddenly withdrawing it, sets up an electromotive force in one direction or the other in the wire itself. To explain this phenomenon, we have again recourse to the conception of lines of force. It is evident that in approaching the magnet to the coil we move not only the metal alone, but also *all the lines of force which surround it,* and in so doing we cause these lines, or at any rate some of them, to cut the wire of the coil. The same happens if the magnet remains at rest and we move the coil relatively to it; the wire cuts through the lines of force and an electromotive force is set up in it in consequence. We cannot explain the why and wherefore of this action, and must rest content to accept it as abundantly proved by experiment. A careful investigation also shows that the strength of the current, and consequently the amount of electromotive force set up, is directly proportional to the speed of movement and to the strength of the magnet. We conclude from this that the electromotive force is proportional to the rate of cutting lines, that is, to the number of lines cut per second by each wire. It is also proportional to the number of wires in the coil. We also find that in thrusting the magnet into the coil we experience a resistance necessitating the expenditure of mechanical energy, the amount of which is proportional to the product of current and electromotive force. This resistance, and the mechanical energy necessary to overcome it, will be the greater the lower the electrical resistance of the coil, provided other things remain equal, and if the coil be open so that no current can pass, there will be no opposing force to the movement of the magnet. In order to investigate this phenomenon of the creation of electromotive

force by the movement of a conductor in a magnetic field, we will assume the simplest possible case, viz., that of a uniform field, the lines of which we suppose to be vertical. Let two metallic bars be fixed at equal distance from the ground, and parallel to each other, and let a third bar, which we term a slider, be laid at right angles across these bars, and let it be free to move parallel to itself, but always remaining in contact with them. As soon as the slider is set in motion, a difference of potential will be created between its ends where it rests on the bars, tending to make electricity flow from the bar of higher to the bar of lower potential. Such a flow of electricity will actually take place, and can be made visible if the bars be connected by a galvanometer. Let d be the distance between the bars, v the velocity of the slider, and F the intensity of the field, then the difference of potential between the bars, is $F. d. v$, which product also expresses the number of lines of force cut by the slider per second. If the distance between the bars be one centimeter, and the velocity one centimeter per second, and the intensity of the field be also unity, we obtain the unit of electromotive force. We define, therefore, as the *unit of electromotive force, that which is created in a conductor moving through a magnetic field at such a rate as to cut one unit line per second.* Imagine that the bars and the galvanometer connecting them have absolutely no electrical resistance, but that the slider have a resistance r, then by Ohm's law the current produced through the circuit, whilst the slider is in motion, will be

$$c = \frac{F. d. v}{r}.$$

If the intensity of the field is unity ($F = 1$), and if the bars are one centimeter apart, unit current will be pro-

duced at a velocity $v = r$. We find, therefore, that the electrical resistance of the slider, and for the matter of that the electrical resistance of any conductor, can be expressed in the same terms as a velocity. We say that the resistance of a conductor is so many centimeters a second. It is customary to express resistances by reference to a standard resistance, *the ohm*. The relation between this and the unit of resistance in absolute measure will be shown presently. Before doing so, we must, however, say a few words about the energy required to move the slider, and about the relation between current and mechanical force. Let P represent the pull in dynes required to move the slider across the lines of a field of intensity F, with a velocity of v centimeters a second. The energy expended in ergs will evidently be

$$W = P.\,v.$$

By the principle of the conservation of energy, this must be equal to the electrical energy produced. The question which now presents itself is the determination of the electrical energy of a current, c, flowing under a difference of potential of $F.\,d.\,v$. We have up to the present used the term potential without giving its definition. As the name implies, the potential of a body is its property of allowing energy stored up in it to become potent, that is, to do work. If a weight be raised to a certain height from any given datum level, the mechanical work thereby expended can be recovered by allowing the weight to descend again whilst overcoming the resistance of some piece of mechanism which can be made to do useful work. In its elevated position the weight has, therefore, a certain potential energy, which is equal to the product of the weight multiplied by the distance to which it has been raised. If the weight be unity, this product is

numerically equal to the height, and we can say that the mechanical potential of a heavy body raised to a certain height above datum level equals the mechanical energy required to lift unit weight to the same height. By multiplying the potential thus defined with the weight of the body we obtain the total mechanical energy which it is capable of exerting. Similar reasoning applies with regard to the transfer of electricity. It is well known that two bodies charged with electricity of the same sign repel each other, and if one of the bodies is fixed whilst the other is being approached to it mechanical energy must be expended in the act of approaching. This energy can again be recovered (provided there were no losses by dissipation of electricity into the surrounding air) by allowing the movable body to recede from the body at rest whilst doing useful work. To fix ideas, let the stationary body be a very large metallic sphere charged with a certain amount of positive electricity, and let the movable body be a very small gilded pith ball charged with a unit of positive electricity. We assume a great difference in the size of these bodies in order that the charge on the larger body shall not be sensibly altered by the variation of position of the small body. If we remove our pith ball to an infinite distance, so as to be completely beyond the repulsive action of the larger body, we can consider it to be in that position analogous to unit weight placed at datum level. If we now advance the pith ball up to the large sphere, we shall have to perform mechanical work, and, according to Sir William Thomson's definition, the electrical potential of the sphere is measured by the amount of mechanical work performed. If, instead of starting from infinite distance, we had started from another sphere having a different

potential to the first, the mechanical work performed in the transfer of the pith ball would be a measure of the *difference of potential* between the two spheres. It will appear self-evident that if, instead of only one pith ball, we transfer two, three, or more, or if the charge of the pith ball, instead of one unit, were two, three, or more units of electricity, the mechanical energy would also be increased in the same proportion. From this it follows that the mechanical energy required to transfer q units of electricity from a sphere or point where the potential is p_1 to a sphere or point where the potential is p_2 will be—

$$-q(p_1 - p_2)$$

and this result will not be altered if the transfer, instead of taking place by the aid of our pith ball conveying a definite electrical charge q, were to take place by means of a wire carrying a continuous current, since the latter can be considered as a succession of pith balls. In our experiment with the slider, c is the current or quantity of electricity transferred in one second, and the mechanical energy represented by the current during the interval of one second is therefore

$$c\,F\,d\,v,$$

which by the principle of the conservation of energy must be equal to the mechanical energy expended during one second in moving the slider. We find, therefore, the relation

$$P = c\,F\,d.$$

The mechanical force experienced by a straight conductor d centimeters long, carrying a current c, and situate in a uniform field of intensity F, the lines of which are at right angles to the conductor, is equal to the product of length of conductor, current, and intensity of field. This relation is

of the utmost importance for the construction of electromotors, inasmuch as the mechanical forces thus determined are the real source of power of these machines. It would, therefore, be desirable to verify the expression obtained above by some other method of reasoning, and this can easily be done if we go back to what has been said about the relation existing between a current and the force exerted by it on a free magnet pole. It was then stated that experiments have shown the force to be equal to the product of length of conductor, current, and strength of pole, divided by the square of the distance. We assume hereby that the conductor stand at right angles to the line joining its centre with the pole, and that it be very small in comparison to the distance from the pole. All the straight lines which can then be drawn from the pole to different points of the conductor intersect it at right angles, and can be considered to be parallel. The conductor lies, therefore, in a uniform magnetic field of the intensity $F = \frac{m}{R^2}$, m being the magnetism of the free pole, and R its distance from the conductor. Let d be the length of the conductor, c the current, and P the mechanical force exerted on the pole, we have

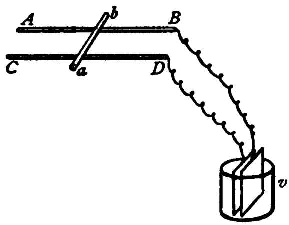
$$P = \frac{m\,c\,d}{R^2},$$

as has already been shown. But since action and reaction must be equal, the conductor acts upon the pole with precisely the same force as that exerted by the pole on the conductor; and we find that the force tending to lift the conductor out of the plane laid through it and the pole is also equal to P. By substituting F for $\frac{m}{R^2}$ we have

therefore $P = c\ F\ d$, the same expression as obtained above.

Returning now to the above example of the two horizontal bars and the slider laid across them, let, in Fig. 8, *A B*, *C D*, represent the two bars, *a b* the slider, and *V* a voltaic cell connected to the bars by wires, as shown. The lines of force—not shown in the diagram—are supposed to be vertical, and therefore at right angles to the slider and to the bars. From what has been stated above, it will be seen that on establishing connection with the voltaic cell, the current flowing through the slider will

Fig. 8.



generate a force tending to move it along the bars parallel to itself. This force could be utilized by attaching a cord to the slider, which, passing over a pulley, could be made to raise a weight. We have here the most simple case of transforming electrical into mechanical energy. As soon as the slider begins to move, it cuts through lines of force, and, as was explained above, by this action a difference of potential is created at its ends, or, as we can also express it, the slider becomes the seat of an electro-motive force. A moment's reflection will show that this electro-motive force must be directed in opposition to the electro-motive force of the cell, for, were it not so, the original current would be in-

creased by the creation of this second electro-motive force, and we should thus obtain additional electrical energy and mechanical energy at the same time, which is clearly incompatible with the principle of the conservation of energy. If in a circuit there are two electro-motive forces, the current resulting from their combined action is proportional to their sum. Since, in this instance, the electro-motive force of the slider is opposed to that of the cell, we must consider it to be negative, in fact a *counter-electro-motive force*, and the resultant electro-motive force in the circuit will be $E—e$, if by E we denote that of the cell and by e that of the slider. The resultant current is therefore found by dividing $E—e$ by the total resistance of the circuit. As the slider moves along the bars, this resistance is evidently constantly increasing or diminishing, according to the direction in which movement takes place. Not to complicate the problem by the introduction of a variable resistance, we shall therefore assume that the bars are so thick as to have practically no resistance, and in that case the total resistance will consist only of that of the slider, the connecting wires, and the cell. Let that be r as before, and we find the current $c = \frac{E—e}{r}$ by Ohm's law.

The mechanical energy exerted in raising the weight P with a velocity of v is per second: $W = P v$; and that must be equal to the electrical energy which is the product of current and difference of potential between the ends of the slider. Let, as before, F represent the intensity of the field, and d the length of the slider, we have:

$$W = c\, F\, d\, v$$

$$W = \frac{E—e}{r} F\, d\, v,$$

and since $e = F\,d\,v$, we have also

$$W = \frac{E - F\,d\,v}{r} F\,d\,v.$$

According to our former definition of intensity of field, F represents the number of unit lines of force passing through one square centimeter of surface between the bars, and $d\,v$ is the surface swept over by the slider in one second. The product $F\,d\,v$ represents, therefore, the number of unit lines cut by the slider per second. If we denote this number by z, we have also the following expression for the mechanical energy represented by the raising of the weight:

$$W = \frac{E - z}{r} z.$$

This formula will be used later on for the determination of the mechanical energy obtainable with a given electromotor. For the present it will be more convenient to retain the symbol e, and we write,

$$W = \frac{E - e}{r} e.$$

Since $e = F\,d\,v$, and $P = c\,F\,d$, we have the relation,

$$P = \frac{c\,e}{v},$$

from which it will be seen that with a constant speed and with a constant current the weight which the slider is capable of hauling up, and therefore its capacity of doing work, is directly proportional to the counter-electromotive force. It will also be seen how mistaken is the notion that counter-electro-motive force in an electromotor is a loss, and that those well-meaning but confused inventors who strive to design motors which shall have as little counter-electro-motive force as possible, so as not to

check the flow of current which works the motor, would, if they were successful, obtain machines which could not give out any power at all.

The energy given out by the cell is $E\,c$, that performed by the slider is $e\,c$, and the efficiency of our simple motor is therefore

$$\eta = \frac{e}{E}.$$

In order to find the condition of maximum work performed, we form the differential quotient of W, and equal it to zero, the variable being the counter-electro-motive force e. That gives,

$$o = \frac{d\,W}{d\,e} = E - e + e\,\frac{d}{d\,e}\,(E - e),$$

$$o = E - 2\,e,$$

$$e = \frac{E}{2}.$$

If the speed of the slider be so regulated that its counter-electro-motive force is equal to half the electro-motive force of the cell, the maximum possible amount of mechanical work will be performed, the efficiency in this case being 50 per cent.

$$W\,max. = \tfrac{1}{4}\,\frac{E^2}{r}.$$

In order to obtain that speed of the slider, we must regulate the weight P attached to the cord, so that,

$$v = \frac{E}{2\,F\,d},\ P = \frac{E\,F\,d}{2\,r},\ \text{and}\ c = \frac{E}{2\,r}.$$

If a heavier weight were attached to the cord, the current would be greater and the speed smaller ; if a lighter weight were attached, the current would be less and the speed greater. In both directions there exists a

limit which will be reached, on the one hand by reducing the weight to zero, when the speed will be a maximum, and, on the other hand, by using so heavy a weight that the slider cannot move at all, when the current will be a maximum. These limiting values can easily be obtained from the above formulas, and are as follows:

Weight completely removed,

$$P = o, c = o, e = E, v = \frac{E}{F d}.$$

Weight just balances force of slider, which remains at rest,

$$P = \frac{E F d}{r}, c = \frac{E}{r}, e = o, v = o.$$

On comparing these expressions with those found for the condition of maximum work, it will be seen that in the latter case the current is half as great as that obtained with the slider at rest, and the velocity half as great as that of the slider with the weight removed. The statical pull on the slider when doing maximum work is half that obtained with the slider at rest.

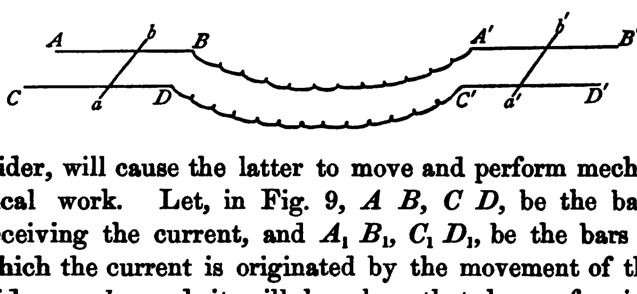
These investigations, although at first sight they might seem somewhat abstruse, because no engineer would think of pulling up weights by the arrangement of a slider as described, are nevertheless of great practical importance. Imagine that, instead of having a single slider, we place a number of wires on the surface of the armature of an electro-motor, and that we arrange to have a very intense field by the employment of steel or electro-magnets with suitable devices for commutating the current in the armature wires, which enable us to transform the rectilinear motion of the slider into a continuous rotary motion; and we obtain at once an eminently practical machine. This machine does not differ in principle from our simple slider,

and all the general laws we have found above for the latter are therefore applicable to the former. Certain allowances will, of course, have to be made on account of the usual mechanical resistances and losses common to all mechanism, and also on account of certain secondary actions and electrical losses or imperfections inseparable from the adaptation of an abstract or ideal machine for actual work ; but, in general, the laws deduced above hold good in practice. Thus we shall find, that if an electro-motor, having permanent field magnets (either of steel, or electro-magnets excited by a constant current), runs at a speed of 1,000 revolutions a minute when doing no external work, whilst supplied with current at a given electro-motive force, it will do a maximum of work when loaded to such an extent that its speed drops to about 500 revolutions a minute, the electro-motive force remaining the same. If loaded more and more, say by the application of a brake, the speed will be further reduced until the armature of the motor comes to a standstill. In this condition, the statical moment of the armature, or the *torque* as it is also called, will be twice as great as when running at 500 revolutions, and the current passing through it will also be twice its former value. This fact is of importance, as it enables us to calculate the *starting power* of the motor, a point of great interest in the application of motors to tramway or railway carriages. We must at once observe that so large a current should never be allowed to pass through the armature for more than a very few seconds ; and when in regular work, motors are generally so loaded as to run faster than half their idle speed, partly because the current corresponding to half-speed would still be excessive, and heat the wires too much, and partly because we are, as a rule, not content

with so low an efficiency as 50 per cent. From the formula for the efficiency given above, it will be seen that the nearer the counter-electro-motive force approaches to the electro-motive force of the source of current (a voltaic cell in our example), the nearer does the co-efficient of efficiency approach to unity. But to obtain a high counter-electro-motive force we must allow the motor to run at a high speed.

It has already been shown how a slider, when moved across the lines of a magnetic field over two metallic bars, can be made to produce a current in a wire joining the two bars. It has also been shown how a current sent from an external source into the bars, and through the

Fig. 9.



slider, will cause the latter to move and perform mechanical work. Let, in Fig. 9, $A\ B$, $C\ D$, be the bars receiving the current, and $A_1\ B_1$, $C_1\ D_1$, be the bars in which the current is originated by the movement of the slider $a_1\ b_1$, and it will be clear that by performing mechanical work on the latter slider, we can cause the slider $a\ b$ to give out mechanical work by raising a weight, as explained above. We have here the most simple possible case of the electrical transmission of energy. The generating system, $A_1\ B_1$, $C_1\ D_1$, can be at any distance from the receiving system, $A\ B$, $C\ D$, and all that is required are electrical connections (wires to carry the current) between A_1 and B, and between C_1 and D. Let the intensity of the magnetic field be F_1 at the

generator and F at the receiver, and let the pull applied at the generating slider be P_1, whilst that exerted by the receiving slider is P; let also v_1 and v be respectively their velocities, and e_1 and e respectively the electromotive forces, then the following equations evidently obtain:

$$c = \frac{e_1 - e}{r},$$

$$e_1 = F_1\, d_1\, v_1,$$

$$e = F\, d\, v,$$

$$P_1 = \frac{F_1\, d_1\, v_1 - F\, d\, v}{r}\, F_1\, d_1,$$

$$P = \frac{F_1\, d_1\, v_1 - F\, d\, v}{r}\, F\, d,$$

$$\frac{P_1}{P} = \frac{F_1\, d_1}{F\, d}.$$

This equation shows that the pull exerted on the generating slider, and that given out on the receiving slider, bear a fixed proportion to each other which is independent of the speed, but depends on the intensities of the fields and on the dimensions d_1 d of the sliders. The energy expended at the generating system is

$$W_1 = F_1\, d_1\, v_1\, \frac{F_1\, d_1\, v_1 - F\, d\, v}{r},$$

and that given out by the receiving system is

$$W = F\, d\, v\, \frac{F_1\, d_1\, v_1 - F\, d\, v}{r}.$$

The ratio between the two, or the efficiency of transmission, is evidently

$$\eta = \frac{F\, d\, v}{F_1\, d_1\, v_1}.$$

If both systems are identical as regards dimensions and

strength of field, $n = \frac{v}{v_1}$. This would be the case where two identical dynamos are employed, the one as receiver and the other as motor, both machines being series wound, so that the same current circulates around both sets of field magnets. In such cases it has been customary to determine the electrical efficiency of the transmission of energy by simply determining the speeds, and taking their ratio. If no losses and no secondary actions would occur in the connecting wires and in the machines, no objection could be raised to this way of determining the efficiency; but in practice there are some very serious objections to this method. In the first place, the two magnetic fields, although produced by the same magnetizing power, are not of absolutely equal intensity, because the magnetization of the armature produced by the current circulating through its coils has a certain influence in altering the intensity of the magnetic field, and this alteration is different in a motor to what it is in a dynamo. In the second place—and this is a fatal objection—any leak or loss of current taking place at some intermediate point in the wires by which the machines are connected, instead of lowering the efficiency, as determined by the speeds, has actually the effect of making it appear higher than it really is. This will become obvious by reference to the equation for the counter-electro-motive force of the receiving machine. Since $e = F\, d\, v$, any reduction in F, consequent upon the loss of some of the magnetizing current through a leak in the line, has naturally the effect of increasing v, the velocity of the receiving machine, and thus it may happen that through the development of a fault in the insulation of the line the ratio of speeds will increase, thus showing apparently

an increase of efficiency, whereas in reality the system has become less efficient. The variables in the above equations are v, v_1, P, and P_1; the dimensions of the machines (or sliders) d and d_1, and the intensities of the fields being constant. Since the ratio between the static efforts, P and P_1, is also a constant, the number of variables is reduced to three, and, if two of these are given, the third can be found. As an example, we will take the case that the load P to be put on the receiving machine shall be given (say, for instance, the pull required to haul up a train on a steep gradient, but neglecting for the moment the difference in pull caused by variations of speed) and the speed v_1 of the generating machine shall also be given. We require to know the power necessary to drive the generating machine, and the speed and energy developed by the receiving machine. From the equation for P, we find immediately the speed of the receiving machine,

$$v = v_1 \frac{F_1 d_1}{F d} - \frac{r P}{F^2 d^2}.$$

As will be seen, this speed is not directly proportional to the speed of the generator, and if the latter be increased the speed of the receiver will increase in a somewhat faster ratio. Since the ratio of speeds enters into the formula for the efficiency, it will be evidently advantageous to work the machines at the highest possible speed consistent with mechanical safety. On the other hand, if we lower the speed of the generator beyond a certain point the receiver will not be set in motion at all.

This will happen if $v_1 \frac{F_1 d_1}{F d} = \frac{r P}{F^2 d^2}$,

$$v_1 = \frac{r P}{F d F_1 d_1}.$$

In this case the efficiency is zero. The minimum speed of the generator is therefore dependent on the dimensions of the two machines and on the strength of the two fields, and is inversely proportional to the product of these four quantities.

The mechanical energy which has to be applied to the generator is $W_1 = P\, v_1 \frac{F_1\, d_1}{F\, d}$,

and that obtained from the receiver is

$$W = P\, v_1 \frac{F_1\, d_1}{F\, d} - \frac{r\, P^2}{F^2\, d^2},$$

the difference between the two being lost. This loss, which is represented by the expression $r\left(\frac{P}{F\, d}\right)^2$, we must regard as energy transformed in a way not suitable for the purpose in view. Since it does not appear in the shape of mechanical energy we must expect to find it appearing in the shape of heat, and this is indeed the case, as can easily be proved. It has been pointed out above that the static pull is the product of current, field-intensity, and the dimension of the machine. The quotient $\frac{P}{F\, d}$ represents, therefore, nothing else but the current flowing through the circuit, and the above term for the energy lost can also be written in the form

$$r\, c^2,$$

which, as is well known, represents the heat developed by the passage of the current c through a circuit, the electrical resistance of which is r. Thus the whole of the energy applied at the generator is accounted for, partly by that given out by the receiver, and partly by that used up in heating the circuit. It need hardly be mentioned that the formulas given here for the transmission

of energy refer to ideal machines which are free from all other losses, both mechanical and electrical, but that in actual practice these other losses cannot be neglected, and considerably complicate the problems to be solved. The author, nevertheless, has thought it advisable to enter at some detail into the case of transmission of energy by means of ideal machines, not because the formulas obtained are immediately applicable to practical cases, but because they form the basis of other formulas suitably altered for practical purposes, and which will be given in a subsequent chapter. The example cited is also intended to show how easily and simply the system of absolute electro-magnetic measurement can be applied to apparently complicated problems. Before leaving this subject we must refer to the relation between electrical units in absolute measure and those units commonly used in practice. The units as given in the centimeter-gram-second system are of inconvenient magnitude for practical purposes; some of them are so small that millions and even larger figures are required to express quantities commonly dealt with in practical work, and others are, again, so large as to necessitate the use of fractions. We had already occasion to refer to the three units most often occurring in electro-mechanical problems, viz., current, electro-motive force, and resistance. The unit of quantity of electricity has also incidentally been mentioned as represented by that amount of electrical matter which a given current conveys in one second. For the sake of completing the list we must also mention a property of conductors called their *capacity*, by which term we mean their capacity or power to hold an electrical charge. The capacity is measured by the quantity of electricity with which a body can be charged under an

electro-motive force equal to unity. The relation between the so-called practical units and their equivalents in the centimeter-gram-second system is as follows :—

Name of Electrical Quantity.	Practical Unit.	Equivalent c. g. s. Unit.
Current strength . .	Ampere . .	10^{-1}
Electro-motive force .	Volt . . .	10^{8}
Resistance . . .	Ohm . . .	10^{9}
Quantity of electricity .	Coulomb . .	10^{-1}
Capacity . . .	Farad . .	10^{-9}
	Microfarad .	10^{-15}

CHAPTER II.

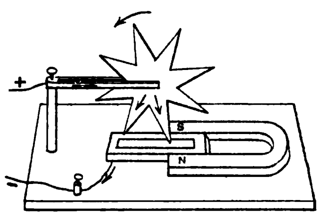
First Electro-motor—Professor Forbes' Dynamo—Ideal Alternating Current Dynamo—Ideal Continuous Current Dynamo—Siemens' Shuttle-Wound Armature—Effect of Self-Induction—Experiments with Electro-motors—Hefner-Alteneck Armature—Gramme Armature—Pacinotti Armature—Electro-motive Force created in any armature.

In the preceding chapter it was shown how mechanical energy can be converted into that of an electric current, and how the electric energy represented by a current flowing under a given difference of potential can be reconverted again into mechanical energy and do useful work. The apparatus employed for this double conversion was assumed to be of extremely simple form, in order to limit our investigation to the fundamental laws without obscuring these laws by the introduction of secondary actions and losses. It will now be necessary to confront the subject from a somewhat more practical standpoint, and to show how the conversion between mechanical and electrical energy can be obtained with machinery of a practical form. As a first step towards a practical solution of the problem to produce motive power by an electric current, we must consider Barlow's wheel,[1] invented by Sturgeon and Barlow about sixty-five years ago. A star-shaped wheel was mounted on a horizontal

[1] Barlow, "On Magnetic Attraction." London, 1823.

axis and set over a trough containing mercury in such way that during rotation of the wheel one or two spokes were always dipping into the mercury. Fig. 10. A permanent steel magnet *N S* was placed in such position that the lines of force joining its two poles passed transversely across the plane of rotation of the wheel, and upon sending a current through the wheel in the direction indicated by the arrows, rotation was produced in the opposite sense to the hands of a watch as seen from the side on which was placed the *N* pole of the magnet. It will be seen at a glance that this apparatus is nothing else

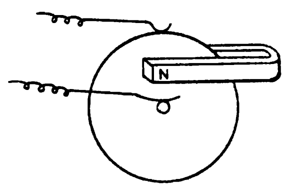
Fig. 10.



but our arrangement of a slider in rotary form, the lines of the magnetic field being in this case horizontal where they cut through the wheel. Each spoke is a slider coming successively into action as its extremity touches the mercury in the trough and is thus put in electrical connection with the rest of the circuit. It was also found that the experiment succeeded if, instead of a star wheel, a plain metallic disc was employed, the lowest point of the circumference just touching the mercury. In 1831 Faraday reversed the experiment and obtained an electric current from a disc rotating between the poles of a magnet. Fig. 11. The magnet was so placed that the induction between the poles, that is, the lines of force

passing from one pole to the other, should pierce the surface of the disc, and the current was taken off by contact springs on the axis and on the circumference; the latter being placed on the radius of greatest induction. Lately Professor George Forbes has constructed dynamos on the same principle, the only difference being that, instead of using a permanent steel magnet, he uses an electro-magnet which becomes excited by the current produced. Professor Forbes' machine[1] is remarkable for the very powerful current it produces as compared to its

Fig. 11.

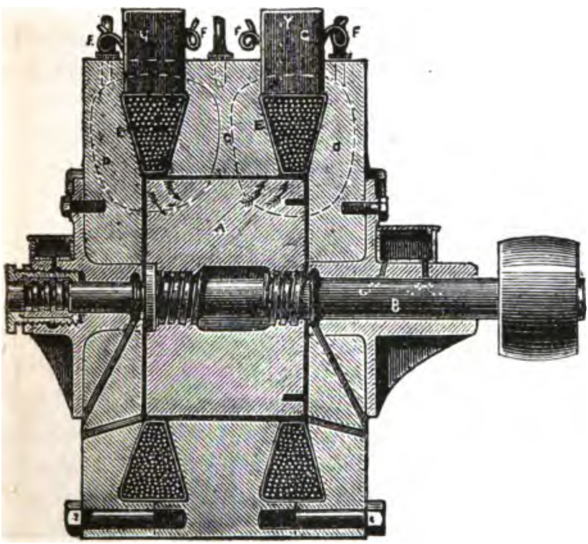


small size. He has devised several modifications, but for our purpose it will be sufficient to describe one of his arrangements. The armature of this dynamo, which is illustrated in Fig. 12 in longitudinal section, consists of a wrought iron cylinder without any wire on it. The field magnet is a closed iron casing surrounding the armature on all sides, and containing two circular grooves of tapering section into which are laid the exciting coils *E*, formed of insulated copper wire. If a current passes through these coils, it produces lines of force which completely surround each coil, and which pass partly through the iron shell *C D* forming the field magnet, and partly through the armature *A*. The general character of

[1] See "The Engineer" of July 17, 1885. The author is indebted to the editor of that paper for the use of the engraving.

these lines is shown by the dotted curves. It will be seen that as the armature cylinder revolves it will become the seat of electro-motive forces acting at right angles to the lines, as indicated by the arrows, and if we provide rubbing contacts at the ends of the cylinder we can obtain the current due to these electro-motive forces. The

Fig. 12.



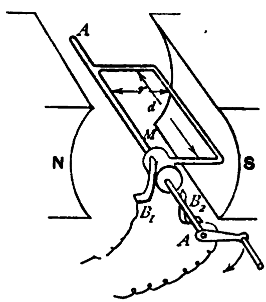
FORBES' NON-POLAR DYNAMO.

contacts are arranged at the inner periphery of the exciting coils, and consist of a series of carbon blocks held in two copper rings, which are connected to the two terminal plates *G G*. The current is thus taken off all around the armature, and the latter contains absolutely no idle portion. This is one of the reasons why the machines are so powerful as compared to their size. The other reason is that the intensity of the magnetic field is

very great. As will be shown in a subsequent chapter, when the theory of continuous current motors will be given, the intensity of the magnetic field is the greater the smaller the clearance between the polar surface of the magnet and the core of the armature. In motors or dynamos, which contain copper wire coiled over the armature core, this clearance is necessarily greater than in Professor Forbes' dynamo, where the space between armature and magnet is just sufficient to allow of free rotation. The following figures will serve to give an idea of the relation between the size of these machines and their output of electrical energy. A dynamo having an armature six inches in diameter and nine inches in length, will, when driven at a speed of 2,000 revolutions a minute, give a current of 5,000 Amperes at a difference of potential of two Volts. According to the inventor, an armature four feet in diameter by four feet in length would produce an electro-motive force of sixty Volts when driven at a speed of 1,000 revolutions a minute. If we were to allow the current to increase in the same proportion as the area of the armature cylinder, this machine could produce 320,000 Amperes, and would require about 30,000 h.-p. to drive it. The employment of such an enormous power and at the high speed of 1,000 revolutions is of course out of the question, but on purely theoretical grounds it is interesting to notice how easily our simple experiment of the slider when suitably arranged in rotary form will lead to results which on account of their magnitude are quite beyond the capability of modern engineering. Dynamos similar to that just described are generally called *Uni-polar Dynamos*. Professor Forbes prefers the title *Non-polar Dynamos*, and with good reason, for, as was pointed out already in the

first chapter, a magnet with only one pole is a physical impossibility. All the dynamos of this class have the disadvantage of requiring to be driven at a very high speed in comparison to the electro-motive force they can produce. The reason lies in this, that the length of conductor cutting through the field is limited by the size of the armature. These machines are practically nothing else but dynamos having only one turn of wire wound on their armature core. An ideal machine of this kind is shown in Fig. 13. The field magnets *N S* are placed

Fig. 13.



IDEAL ALTERNATING CURRENT DYNAMO.

horizontally opposite each other, and their polar surfaces are bored out to form a cylindrical cavity within which one single turn of wire can be revolved by means of a crank. One end of the wire is joined to the axis *A A*, and the other to a metal sleeve *M*, rubbing contact springs B_1 B_2 being arranged in order to take the current off the sleeve and axis respectively. The lines of force pass horizontally across the cylindrical cavity from *N* to *S*, and those which are contained within the space swept by the wire are cut twice during each revolution. The effect is the same as if we had attached our slider to

a crank and by turning the latter had caused the slider to assume a reciprocating motion across the lines of the field. In that case, when the crank is vertical, that is, parallel to the lines of the field, the speed of the slider is a maximum, and therefore its electro-motive force is also a maximum. As the crank approaches either of its dead points, where it is horizontal, the speed of the slider and its electro-motive force diminish and become zero at the moment the motion is reversed. From what was said in the preceding chapter, it will also be seen that the direction in which the electro-motive force acts depends on the direction of motion, and the current produced must therefore be alternating. If we plot the angles of the crank on the horizontal, starting from any given position, say, for instance, from its position at the end of the stroke, and the electro-motive forces on the vertical, we obtain a graphic representation of the relation between these two quantities. In a uniform field, where the electro-motive force depends only on the speed of the slider, but not on its position in the field, the electro-motive force is evidently proportional to the sine of the angle of the crank, and is given by the expression

$$E = F\, d\, \omega \sin \alpha,$$

where ω is the circumferential speed of the crank, and α its angular position, the other symbols being the same as before. It will be seen that $E = o$, for $\alpha = o$ and $\alpha = \pi$, whilst for $\alpha = \frac{\pi}{2}$ or $\alpha = -\frac{\pi}{2}$, E attains its greatest numerical value, being positive or negative according to the sign of the angle. The same relations obtain in the ideal alternating current dynamo, Fig. 13. If the crank is in the position shown, the wire is in the middle of the S pole piece and cuts the lines of force at maximum speed; if the crank is

vertical, the wire moves parallel to the lines, and its rate of cutting lines is zero. This position corresponds to the end of the stroke with an oscillating slider. When the crank is again horizontal, but pointing to the left, the wire is in the middle of the *N* pole piece, and again its speed across the lines, or its rate of cutting lines, and the electro-motive force are maxima, but the current will be in an opposite direction to what it was at first. If the crank be turned in the direction indicated by the arrow, the current will leave the machine at the contact spring B_1 during the time the crank is on the right-hand side of the vertical diameter, and it will flow from B_2 through the external circuit, and enter the machine at B_1 during the time the crank is on the left-hand side of the vertical diameter. Let n be the number of revolutions per minute, then $\frac{n}{60} 2 \pi r = \omega$, the circumferential speed of the wire, and the maximum of electro-motive force, irrespective of sign, is evidently

$$E = F d \frac{n}{60} 2 \pi r.$$

Now $2 r d$ is the total space swept by the wire, and $F 2 r d$ is the total number of lines passing through that space; let z be that number, and we find for the maximum of electro-motive force the expression,

$$E = z \pi \frac{n}{60} \quad \ldots\ldots\ldots\ldots 1$$

During one half revolution the electro-motive force increases from zero to this maximum, and then decreases again to zero. As far as practical applications of the dynamo are concerned, it is not the maximum electro-motive force which we require to know, but the *mean electro-*

motive force, which acting during the same time as the variable electro-motive force, would cause the same quantity of electricity to flow through the circuit. Let, at any given moment, the wire occupy a position defined by the angle α from the vertical, and let it advance through an angle $\delta\,\alpha$ during the time $\delta\,t$, then the quantity of electricity flowing through the whole circuit of resistance R is evidently

$$\delta\,q = \frac{F\,d\,\omega\,\sin\alpha\,\delta\,t}{R},$$

and since $\omega = r\,\frac{\delta\,\alpha}{\delta\,t} \ldots . \delta\,q = \frac{F\,d\,r}{R}\ \sin\alpha\,\delta\,\alpha.$

During one half revolution α increases from zero to π, and the integral of the above expression taken between these limits gives

$$q = 2\,\frac{F\,d\,r}{R}.$$

The time occupied in this transfer of q units of electricity is $t = \frac{\pi\,r}{\omega}$, and if, during that time, a constant electro-motive force E^1 were acting, the quantity transferred would be $\frac{E^1}{R}\,\frac{\pi\,r}{\omega}$. If this quantity is equal to q, we consider E^1 the average electro-motive force, and its value is given by the equation

$$E^1 = \frac{2}{\pi}\,F\,d\,\omega.$$

Since $F\,d\,\omega$ is the maximum electro-motive force generated at the moment when the wire is cutting the lines of the field at right angles, we have also

$$E^1 = \frac{2}{\pi}\,E.$$

Inserting the value for E from equation 1, we find the average electro-motive force

$$E^1 = 2\,z\,\frac{n}{60} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 2$$

z being, as before, the total number of lines contained in the space swept by the wire, whilst $\frac{n}{60}$ is the number of revolutions per second.

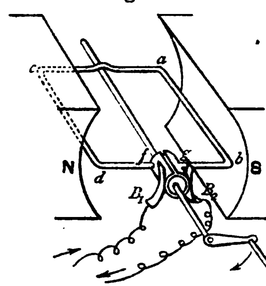
In the ideal alternating current dynamo represented in Fig. 13, the wire in which the currents are generated is arranged to one side of the spindle only. We could easily improve the design by carrying the wire symmetrically to the other side of the spindle, but insulated from it, and attach its end to a second metal sleeve insulated from M. The contact spring or brush B_2 would then have to be set so as to touch this second sleeve, and since the electro-motive forces created in the two wires are at any moment in the same direction as regards the circuit—although opposite as regards a fixed point in space—this improved dynamo with two wires will give double the electro-motive force of the original arrangement. We could still further increase the electro-motive force by coiling the wire several times round the axis, forming a rectangular coil, each convolution being insulated from its neighbours, and if the number of turns counted on both sides of the spindle is $N t$, the average electro-motive force will be

$$E^1 = 2\,z\,\frac{n}{60}\,N t.$$

For most practical purposes, and especially for the transmission of energy, alternating currents are, however, not so convenient as continuous currents, and to produce them it will be necessary to add to our dynamo a device

by which the currents are all directed to flow in the same sense as far as the external circuit is concerned. Such a device is the *commutator*, and its action can be explained by reference to Fig. 14. In the position shown, the electro-motive force created in the wire *a b* will be directed towards the observer, and that created in the wire *c d* will be directed from the observer. The ends of these wires are joined at the back by a cross connection *a c*, and at the front by two wires *d f* and *b g*, to the two halves of a metal cylinder, which for the purpose

Fig. 14.

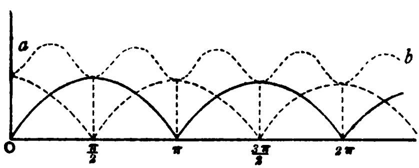


IDEAL CONTINUOUS CURRENT DYNAMO.

of insulation are secured on a wooden hub. The electromotive forces created in *d c* and *a b* tend to draw a current from the line in the direction of the arrow to the brush B_1, thence through *f d*, *c a*, *b g*, to the brush B_2, and out again into the external circuit. This process will go on until the crank reaches the lower vertical position, the strength of the current meanwhile decreasing to zero. When the crank is vertical, each brush touches simultaneously both halves of the metal cylinder or commutator, as it is technically termed, and a moment later the connections become reversed, the brush B_2 now touching the half cylinder to which the wire *f* is at-

tached, and the brush B_1 touching the half cylinder to which the wire g is attached. But, at the same time, the direction of electro-motive force in the two wires has been reversed, the wire $c\ d$ entering the right-hand side of the field, and $a\ b$ entering the left-hand side. Consequently the external current flows in the same direction as before, growing from zero to a maximum when the crank stands horizontally on the left, and again diminishing to zero when it is vertical. Graphically represented, the current is of the character shown by the curve, Fig. 15, the abscissæ being consecutive angles of the crank, and the ordinates being proportional to the sines of these angles.

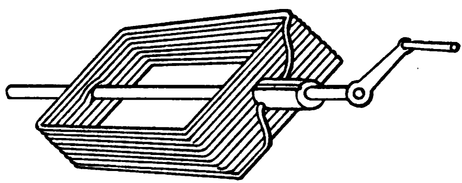
Fig. 15.



It should be noted that the reversal of current always takes place when the electro-motive force is zero, and consequently the change in the contact with the brushes from one commutator plate to the other takes place without sparking. To increase the power of the machine, we can replace the single rectangle of wire by a coil of many turns. Fig. 16. Hitherto we have tacitly assumed that the space contained within the wire coils forming the armature contains air or other non-magnetic substance. The lines of force passing between the polar surfaces $S\ N$ have to leap across a considerable air space, and if by some means we could shorten that portion of their path which lies entirely in air, we would facilitate the flow of lines and increase the strength of the magnetic

field. Roughly speaking, we may take it that air offers to the lines of force about 700 times the resistance of iron, and if we can contrive to fill part of the space between the polar surfaces with iron, a considerable increase of electro-motive force, and consequently of current, will be the result. The space available for this purpose is that contained within the armature coil; in other words, to increase the power of the machine we must wind the armature coils over an iron core. An early dynamo constructed on this principle is that of Siemens, invented in 1855, and provided with the so-called shuttle-wound armature. The core consists of an iron cylinder

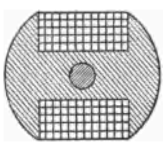
Fig. 16.



provided with two deep longitudinal grooves placed opposite so that the cross-section resembles a double T with rounded heads. The wire is wound into these grooves, and the two ends of it are joined to the plates of a two-part commutator. Fig. 17 shows a cross-section of this armature. In the first machines the core was in one solid piece, but it was found to heat considerably on account of internal currents. It is well known that if a solid body of metal be rapidly rotated between two powerful magnet poles it becomes hot. The reason for this phenomenon is that the outer portions of the metal in cutting through the lines of force become themselves the seat of electro-motive forces acting at right angles to the direction of motion and to the lines, and powerful

currents are started parallel to the axis which run in opposite directions, up on one side and down on the other side of the axis. In a solid armature core there is nothing to check the flow of these currents but the resistance of the metal, which, on account of the large cross-sectional area, is extremely low. These wasteful currents are consequently very strong, and not only absorb much power, but they also weaken the current generated in the copper wire by induction. To avoid their creation, it is necessary to subdivide the mass of the core by planes at right angles to the axis, and to insulate as much as possible the subdivided portions from each

Fig. 17.



SIEMENS SHUTTLE-WOUND ARMATURE.

other. This can be done either by cutting deep narrow circular grooves in the core, or by building it up of thin discs insulated from each other either by paper discs or by being coated with some insulating paint. These armatures are not much used for dynamos at the present day, having been replaced by more perfect forms to be described presently; but they are still extensively employed for small electro-motors. By referring to Fig. 15 it will be seen that the counter-electro-motive force of these motors is a variable quantity depending on the angular position of the armature. If the heads of the double T core are opposite the field magnet poles, the coil is at right angles to the lines of force and the counter-electro-motive force is zero. This happens precisely at the moment

when the brushes touch simultaneously both plates of the commutator, and are therefore short circuited. A current sent through the motor while at rest in this position cannot start it, and this condition is expressed by saying that the armature has two dead points. When at work the momentum of the armature is sufficient to carry it over the dead points, and, apart from the inconvenience to have to start the motor occasionally by hand, these dead points present no mechanical imperfection. But it might be thought that they present a serious electrical imperfection for the following reason: The strength of the current which is allowed to pass through the motor at any given moment depends partly on the electrical resistance of the motor, and partly on its counter-electro-motive force at that particular moment. But since at the dead points there is no counter-electro-motive force, the strength of the current will be a maximum, whilst at those moments the mechanical energy produced is nil. We assume here that the motor is fed by a current flowing under a constant electro-motive force, which is the case most commonly met with in practice. We have now to distinguish between two cases: the motor may be either series wound or shunt wound. If the former, the current in passing through the motor whilst the armature is at a dead point has only to overcome the resistance of the field magnet coils. If the armature is in the position of greatest counter-electro-motive force the current has to overcome not only that, but also the combined resistance of field magnet and armature coils. In that position the mechanical energy of the armature is at its greatest value, but the strength of the current is a minimum. We find, therefore, on the one hand, that the strength of the field magnets (which depends on the current) is least at

the very moments when the armature is in a position to exert most power, and on the other hand, that it is greatest when the armature is at its dead points and cannot exert any power. From the foregoing we should expect that twice during each revolution a great waste of current must take place when momentarily the brushes are short-circuited by the commutator. Although the time during which such short circuits lasts may appear to our senses very brief, it would in comparison with the speed of electric phenomena be still considerable, and have an appreciable effect on the economy of the motor. But there is one circumstance which greatly tends to mitigate the evil effect of the dead points just described, and this is the property of electric currents called *self-induction*. It can best be described as a kind of inertia opposing any sudden change in the strength of the current. If a circuit contains a coil of wire surrounding iron, as in the present case, the field magnets, the self-induction is so great that it requires an appreciable time to change the strength of the current. The increase of current at the dead points is, therefore, checked by this property of self-induction, and the current, instead of being subjected to abrupt and violent changes, becomes simply undulatory. The case is different if the motor be shunt-wound and fed from a source of constant electro-motive force. Since the field magnet coils are excited independently from the current which passes through the armature, their self-induction cannot in any way steady that current, and abrupt changes in its strength and great waste of electrical energy must occur at the dead points. This is a matter of considerable practical importance, and shows that motors with shuttle-wound armatures should never be used coupled up otherwise than armature and field

magnets in series. If it be absolutely necessary to use a motor of that class, the field magnets of which are either permanent steel magnets or are electro-magnets excited independently, the waste can to a certain extent be prevented by inserting into the armature current an electro-magnet which will by its self-induction steady the current. Since this point is of importance, the author has thought it necessary to verify the above theory by experiments. These were undertaken with a twofold object. First, to prove that in a series-wound motor there is no appreciable waste of current at the dead points, and, secondly, to prove that in a motor the field magnets of which are separately excited, such waste occurs. The experiments were carried out as follows. Two small Griscom motors were placed in line behind each other, and their spindles were coupled, so that the armatures stood at right angles to each other, that is to say, when one armature was at its dead point the other was in the position of best action, and its counter-electro-motive force was a maximum. This disposition is represented in Fig. 15 by the dotted curve overlapping that shown in full lines by 90°. The resultant counter-electro-motive force is at any point the sum of the ordinates of the two curves, and is shown by the undulating line *a b*. It will be seen that this curve nowhere touches the horizontal and, therefore, the total counter-electro-motive force of the two motors coupled in series never is zero. An abnormal rush of current at the dead points of any of the armatures can, therefore, not take place. The motors were supplied with a current, the electro-motive force of which was kept as nearly as possible constant during each experiment, whilst the mechanical energy developed was measured on one of the author's absorption dynamometers. The commercial effi-

ciency of the two motors combined was thus ascertained, as shown in Table I. The motors were then coupled parallel, and their efficiency was determined under the same conditions. In this case there were, during each revolution, four dead points, at which the counter-electro-motive force was zero, and when an abnormal rush of current could take place if not checked by the self-induction of the magnet coils. As was to be expected, the current passing through both motors was about double, and its electro-motive force was about half of the former values. But the commercial efficiency was about the same, Table II. One motor alone was then tried, and its commercial efficiency was found to be about the same as that of the two motors combined, Table III. The field magnets of both motors were then excited separately, and the armatures coupled at right angles and connected in series, as per Fig. 15, when the commercial efficiency was found to be rather higher than in the former experiments, Table IV. This is but natural, because the energy necessary to excite the field magnets was not taken into account when calculating the efficiency. The two armatures were then coupled parallel—field magnets still independently excited—and thus during each revolution there were four points where the counter-electro-motive force was zero and waste of current did take place, as is clearly shown by the low efficiency in Table V. One motor alone was then tried under the same conditions and the same result was found, Table VI. These experiments prove conclusively that our above reasoning about the effects of the dead points is correct.

Test of Two Griscom Motors, Numbers 1017 *and* 1027.

Resistance of	N° 1017	N° 1027
Armature	·328	·352
Magnets	·596	·522
Total	·924	·874

Table I. Armatures Coupled at Right Angles, both Field Magnets and Armatures connected in Series.

Revolutions per minute.	Current.	E. M. F.	Foot Pounds on Brake.	Commercial Efficiency %.
2,440	1·31	6·90	0	0
2,368	3·85	18·20	588	19·0
2,440	3·50	16·00	535	21·7

Table II. Armatures Coupled at Right Angles. Each Armature in Series with its Field. Both Motors connected Parallel.

Revolutions per minute.	Current.	E. M. F.	Foot Pounds on Brake.	Commercial Efficiency %.
2,120	2·35	2·94	0	0
2,480	5·25	6·05	206	14·7
2,775	6·60	7·57	432	19·5
2,340	6·80	7·52	366	16·3
2,060	7·50	7·63	450	18·0
2,884	7·90	9·27	748	23·0
2,328	7·60	8·50	578	21·0

Table III. One Motor only. Armature and Field Magnets connected in Series.

Revolutions per minute.	Current.	E. M. F.	Foot Pounds on Brake.	Commercial Efficiency %.
1,980	1·02	4·00	0	0
2,024	4·15	8.20	303	28·0
1,772	4·15	8·40	265	17·0
2,334	4·22	9·25	381	22·3
1,954	3·82	8·10	246	18·0
2,241	3·70	8·25	283	20·9
2,118	3.50	7·60	240	20·5
2,070	5·37	12·00	532	18·6

Table IV. Armatures coupled at Right Angles and Connected in Series. Field Magnets excited separately.

Revolutions per minute.	Current.	E. M. F.	Foot Pounds on Brake.	Commercial Efficiency %.
1,536	1·42	7·20	0	0
2,030	3·30	11·10	370	22·8
1,632	3·10	9·50	300	23·2
2,190	3·70	12·90	483	22·7
2,264	3·93	13·40	500	21·4

Table V. Armatures Coupled at Right Angles and Connected in Parallel. Field Magnets excited separately.

Revolutions per minute.	Current.	E. M. F.	Foot Pounds on Brake.	Commercial Efficiency %.
2,000	3·90	4·40	0	0
3,040	4·50	5·20	0	0
1,094	7·50	5·50	242	13·3
1,746	8·50	6·60	385	15·6
1,680	9·10	7·50	396	13·1

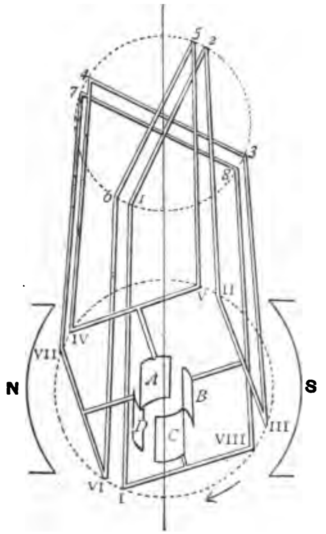
Table VI. One Motor only. Field Magnets Excited Separately.

Revolutions per minute.	Current.	E. M. F.	Foot Pounds on Brake.	Commercial Efficiency %.
1,778	1·65	3·80	0	0
2,330	4·80	5·60	87	7·4
2,422	4·75	5·80	126	10·3

As already mentioned, motors with ordinary shuttle-wound armatures have the disadvantage of requiring to be started by hand if they happen to have stopped on a dead point. They are, consequently, only made of small size, and for larger motor armatures without dead points are used. Such an armature can be evolved out of the simple shuttle-wound pattern by employing two sets of coils placed at right angles to each other. This arrangement is shown in Fig. 18, which represents the Hefner-Alteneck winding invented in 1872. In order to avoid complication the shaft is omitted and the core is indicated by two dotted circles. From what has already been explained it will be seen that in all those wires which at a given moment lie on the right hand side of the vertical centre line, the electro-motive force is directed towards the observer, and in all the wires lying to the left of that line it is directed from the observer. The diameter of commutation joining the points of contact of the brushes with the commutator cylinder will, therefore, be horizontal. In the position shown the negative, or left brush, will touch segment *D*, and the right or positive brush will touch segment *B*. The current enters the armature at the negative brush and splits into two circuits as follows:—One portion goes through VII.,

7, 8, VIII., I., 1, 2, II., and out by the positive segment *B*; the other goes through VI., 6, 5, V., IV., 4, 3, III., and out by the same segment *B*. The two currents are, therefore, in parallel connection. When the armature has turned so far as to bring the segment *C* into contact with the negative brush it will touch for a short time both segments *D* and *C*, whilst the positive brush will

Fig. 18.



HEFNER-ALTENECK ARMATURE.

simultaneously touch *A* and *B*. In this position the wires I., VI., V., II. will be in the strongest part of the field, and the wires VII., IV., III., VIII. will stand on the vertical diameter and contribute nothing towards the total electro-motive force. The current now splits into the following two circuits: From *D* to VI., 6, 5, V., to *A*, and from *C* to I., 1, 2, II., to *B*. In this case the total

electro-motive force is that due to two wires in the position of best action, whereas in all the other positions it is due to four wires. It has been shown above that the average electro-motive force of a loop such as I., 1, 2, II., consisting of two external wires ($Nt = 2$) is

$$E^1 = 2\,z\,\frac{n}{60}\,2.$$

Since two such loops are placed in series, we find the average electro-motive force of the whole armature

$$Ea = 8\,Z\,\frac{n}{60}.$$

But 8 is the number of wires counted all round the armature ; and if, instead of a four-part commutator, we had employed a six-part commutator, and had wound the core with three sets of double coils, we would have three coils in series and the expression for Ea would have been

$$Ea = 12\,Z\,\frac{n}{60},$$

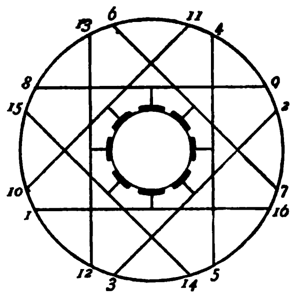
there being twelve external wires on the armature if counted all around. We might thus construct armatures with any even number of external wires. Let Nt be that number, and we have the general expression for the electro-motive force created in the armature of a dynamo, or the counter-electro-motive force created in the armature of a motor:

$$Ea = Nt\,Z\,\frac{n}{60} \quad \ldots\ldots\ldots\ldots \quad 3$$

For the sake of simplicity we have, in Fig. 18, only shown one wire to each coil. It is, however, obvious that by multiplying the turns or wires in each coil the electro-motive force can be proportionately increased. This case is provided for in formula 3, where N signifies the number

of coils, and t the number of turns in each coil, the product of the two being equal to the total number of single wires if counted all around the armature. An armature of the Hefner-Alteneck pattern with eight-part commutator, is shown in Fig. 19. Denoting by Roman figures the ends of the wires on the front end of the armature,

Fig. 19.



HEFNER-ALTENECK ARMATURE.

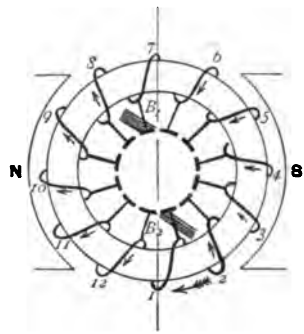
and by Arab figures those on the rear end, the winding is as follows:

From the negative brush to {I., 1, 2, II., III., 3, 4, IV., V., 5, 6, VI., VII., 7, 8, VIII. XVI., 16, 15, XV., XIV., 14, 13, XIII., XII., 12, 11, XI., X., 10, 9, IX.} To the positive brush.

The greater the number of parts in the commutator the more nearly constant will be the electro-motive force and current. This system of winding armatures has the great advantage of utilizing nearly the whole length of the wire, since, with the exception of the cross connections at the ends, all the wire is active. But it has the practical disadvantage that repairs are troublesome to execute. If a fault of insulation should develop in any of the coils,

in order to reach it a large portion of the wire must be taken off, because the coils—especially at the ends—overlap each other in many layers. In this respect the style of armature known as the Gramme, or Pacinotti type, is preferable. A circular iron ring, Fig. 20, is

Fig. 20.

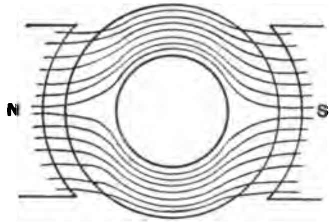


GRAMME ARMATURE.

wound with a continuous helix of insulated copper wire, and certain points of the helix are joined by connecting wires, which in our illustration are shown radial, to the commutator plates. Two brushes, B_1 and B_2, serve as connections between the external circuit and the armature wire. The action of the Gramme armature will best be explained by reference to Fig. 21, which shows the lines of force. It has already been pointed out that iron offers very much less resistance to the passage of magnetic lines of force than air. If there be no armature between the field magnet poles, we assume that the majority of the lines will go straight from pole to pole, Fig. 22. If now a circular core is inserted, their course will be so altered that each line takes the path of least resistance—that is, runs as long as possible in iron, and only leaps across the

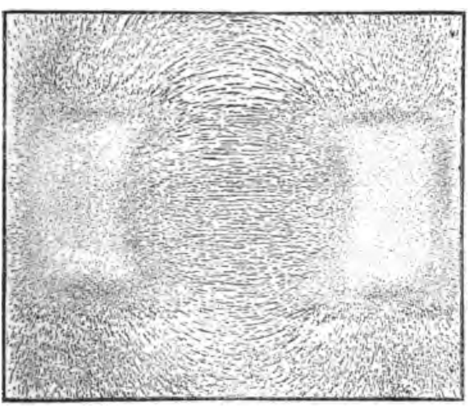
air at the external circumference of the core, because this is the only way in which it can enter the pole piece, Fig. 23. At the internal circumference of the armature

Fig. 21.



there is no necessity for the lines to leave the core, and the central space is therefore almost free of lines. We say almost, because parallel lines exert a repelling action upon

Fig. 22.

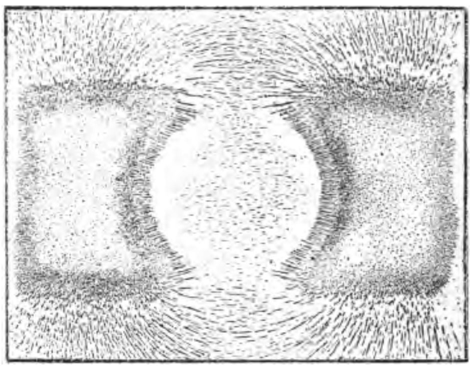


FIELD OF DYNAMO WITH ARMATURE REMOVED.

each other, and it may happen that in case the core is thin, and a large number of lines have to be accommodated, some of them may be elbowed out into the central space,

In well-designed machines the number of lines thus forced across the central space is always so small as to be omissible. The fact of the central space being free from lines ; or, as we may also put it, being shielded by the iron of the core from the influence of the magnet poles is of great importance, since in consequence of it the inner wires of the helix are removed from all inductive action. If this were not the case electro-motive

Fig. 23.



FIELD OF DYNAMO WITH ARMATURE INSERTED.

forces would be created in these wires, which, being opposed to the electro-motive forces developed in the external wires, would weaken the power of the machine. After what has been explained at length with reference to the ideal continuous current dynamo, Fig. 14, it will be easy to trace the direction of electro-motive forces in the external wires of the Gramme armature, Fig. 20. If rotated clock-wise, the electro-motive force will be directed towards the observer in all the wires lying to the right of the vertical centre line, and from the observer in the wires

on the opposite side. The two currents resulting from these forces are indicated by the arrows. In the wires 1 and 7, which for the time being move parallel to the direction of the lines of force, there is no electro-motive force generated, whilst in 4 and 10, which move at right angles to the lines, the electro-motive force is a maximum. By virtue of the continuity of the helix the electro-motive forces in the wires 2, 3, 4, 5, 6 are added, and those in 12, 11, 10, 9, 8 are also added, the two circuits being at all times in parallel connection. The current enters the armature at the brush B_2, which is called negative, then splits into the two circuits mentioned, and uniting again at the brush B_1, which is called positive, leaves the armature, and enters the external circuit. It will be seen from the figure that either brush, when touching two consecutive plates of the commutator, establishes a metallic connection between the beginning and end of the corresponding coil, or, in technical language, short circuits that coil. If the brushes are in the position shown—the neutral diameter on the commutator—the short circuit is perfectly harmless, because there is no electro-motive force in the coil; but if we were to shift the brushes into an active part of the field either to the right or left of the neutral line, each coil, as its extremities pass under the brush, would be traversed by an excessive current, causing heavy sparking at the brush, and probably the ultimate destruction of the armature. The best position at which to place the brushes is always found experimentally; it does not accurately coincide with the geometrical neutral line, but is found to be in dynamos slightly in advance of it, and in motors slightly behind it. Opinions are divided as to the reason of this phenomenon. At one time it was ascribed to a certain sluggishness in the iron

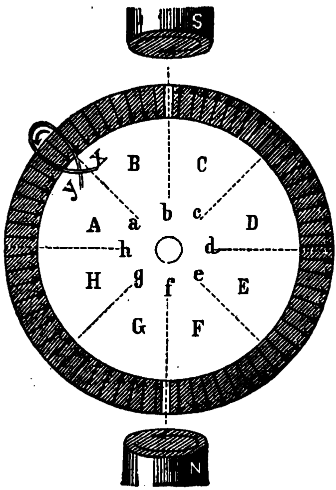
of the core in taking up and losing magnetism, but this theory has long since been discarded by most practical electricians. Some hold that the shifting of the neutral line is due to the magnetizing influence of the armature current upon the iron core by which the latter is transformed into a double horseshoe magnet with like poles joined, and the magnetic axis of which stands nearly at right angles to that of the field magnets. Others again maintain that the brushes must be set forward in a dynamo and backward in a motor, on account of the influence of self-induction in the armature coils. It is probable that both the last-mentioned causes have something to do with the position of the brushes, as will be more particularly explained in Chapter IV.

The first electro-motor having an armature wound on the principle above explained, was constructed by Professor Pacinotti, of Pisa, and the design was published in the journal "Il Nuovo Cimento," in 1864. This machine is illustrated in Fig. 24, and the core of the armature differed only in so far from that employed by Gramme seven years later, as it had external projections between the wire coils, which considerably increased the magnetic attraction between the armature and the pole pieces, thus rendering the machine more powerful. Fig. 25 shows part of the core and winding. The core of the Gramme machine consists of iron wire coiled into a ring of oblong cross-section. After being lapped round with tape for the purpose of insulation, it is wound transversely with cotton-covered copper wire. The winding consists of a number of coils which cover the core completely inside and out, and the beginning of each coil is joined with the end of its neighbour to the same commutator plate. When the winding is completed the armature is driven tight

over a wooden centre by which it is fastened to the spindle.

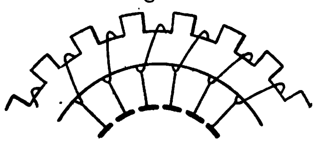
By means of the fundamental formulas established in the previous chapter, we can now determine the electro-

Fig. 24.



motive force of a Gramme armature. Let *D* be its diameter, *b* its length, and *a* the radial depth of the core.

Fig. 25.



PACINOTTI ARMATURE.

Let *Nt* represent the total number of external wires, counted all around the circumference, *t* representing the number of wires corresponding to one plate in the commutator, and *N* the number of plates. If *n* denotes the

speed in revolutions per minute, and z the total number of lines emanating from one pole and entering the half circumference of the armature, then the average electro-motive force created in each wire is by equation 2,

$$E^1 = 2\, z \frac{n}{60}.$$

Since $\frac{N t}{2}$ wires are for the time being connected in series, the average total electro-motive force in the armature is

$$Ea = z\, Nt \frac{n}{60} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 4$$

It might be objected that this expression, which is based on equation 2, will only be correct if the condition under which this equation was obtained is fulfilled in the dynamo. This condition was that the field should be perfectly uniform throughout the space occupied by the armature. In reality this is never the case. The lines are more dense at the corners of the pole pieces, but the exact distribution is not accurately known. A doubt might therefore be entertained whether equation 4 be rigorously true in the case where the intensity of the field is not uniform, but varies in different parts of the field. It will consequently be desirable to deduce the formula for the electro-motive force under the supposition that the intensity of the field in any point on the circumference of the armature, is a function of the angle, α, which the radius to that point forms with the neutral line. What that function is we cannot say, nor is it necessary that we should be able to define it. We only make this assumption: that there shall not be any abrupt change in the strength of the field. We assume that the density of lines varies gradually from place to place. Assume

also the number of wires on the armature so large, that their angular distance $\Delta\, \alpha$ is very small, in fact so small that the intensity of the field can be considered as constant within that angular distance. Since the electro-motive force created in the wires is proportional to their speed, we can determine it for any convenient speed, and if it be required for a different speed, we can obtain it by multiplying the result first obtained with the ratio of the two speeds. In the present instance we fix as a convenient speed that which will bring each wire at the end of one second into the position occupied by its immediate neighbour at the beginning of the second, or

$$v = \Delta\, \alpha\, \frac{D}{2}.$$

This is a very slow speed, and if we wish to know what will be the electro-motive force at the faster speed of n revolutions a minute, we shall have to multiply the electro-motive force at the low speed with the ratio of $\frac{n}{60} \cdot \pi \cdot D$ and v. Since $\Delta\, \alpha\, Nt = 2\, \pi$ we have also $v = \frac{\pi\, D}{Nt}$ and the ratio of the two speeds is

$$\frac{\frac{n}{60}\, \pi\, D}{\frac{\pi\, D}{Nt}} = Nt\, \frac{n}{60}$$

Let $F_1, F_2 \ldots F_{\frac{Nt}{2}}$ be the intensity of the field at the first, second, $\ldots \frac{Nt}{2}$ wire, counted from the neutral line, on one-half of the circumference of the armature, then

the electro-motive force in these wires will be given by the expressions,

$$\begin{aligned} E_1 &= F_1\, b\, v \\ E_2 &= F_2\, b\, v \\ \vdots \quad & \quad \vdots \quad \vdots \; \vdots \\ E_{\frac{Nt}{2}} &= F_{\frac{Nt}{2}}\, b\, v. \end{aligned}$$

The sum of all these forces gives the total electro-motive force created within the armature, which we denote in future by E_a.

$$E_a = \Sigma\, F\, b\, v.$$

But the expression $F_1\, b\, v$ represents the number of lines contained between the first and second wire on the armature, since F_1 is the density, and $b\, v$ the area of the space swept by the first wire in one second. Similarly $F_2\, b\, v$ represents the number of lines between the second and third wire, and so on, the sum of all these expressions representing the total number of lines entering between the first and last wire on one-half circumference of the armature. Let z be that total number, and we find for the electro-motive force at the low speed,

$$E_a = z.$$

At the high speed we have, therefore,

$$E_a = z\, N\, t\, \frac{n}{60}, \quad \dots \dots \dots \dots \quad 4)$$

precisely the same expression as already obtained above. If z be inserted in absolute measure, E_a will also be obtained in absolute measure, and to obtain it in volts the right side of the equation must be multiplied with 10^{-8}. We can also write

$$E_a = \frac{z}{6000}\, N\, t\, n\, 10^{-6},$$

and if we measure the field intensity by means of a unit 6,000 times as great as the absolute unit, we can further simplify the equation to

$$E_a = Z\,Nt\,n\,10^{-6}, \quad \ldots\ldots\ldots \quad 5)$$

Z being the total number of lines in the new system, which is related to the absolute system by the equation

$$Z = \frac{z}{6000}.$$

The cross-sectional area of the armature core is $2\,a\,b$, and if we denote by m the average density of lines per square inch of armature core, we have,

$$Z = 2\,a\,b\,m,$$

and inserting this value in 5), we find for the electro-motive force also the expression,

$$E_a = 2\,a\,b\,m\,Nt\,n\,10^{-6}. \quad \ldots\ldots\ldots \quad 6).$$

This expression is sometimes more convenient than the former, because it enables us at once to see how the dimensions of the armature affect the electro-motive force. Experience has shown that the density of lines, m, in the core cannot exceed a certain limit, which is reached when the core is saturated with magnetism. This limit is $m = 30$, but in practical work a lower density is generally adopted, for reasons which will be explained in the following chapter. A fair average value in good modern dynamos and motors is $m = 20$, and the area, $a\,b$, must be taken as that actually filled by iron, and not the gross area of the core. To avoid waste of power and heating, the armature core of dynamos and motors must be subdivided into portions insulated from each other, the planes of division being parallel to the direction of the lines of force. The space wasted by such insulation must be deducted from the gross area of the core, and the remainder

—from 80 to 90 per cent. of it—is the portion actually carrying lines of force.

The electrical energy developed in the armature, if a current c be flowing through its coils, is $E_a\ c$, and the horse-power represented by this energy is

$$\text{H-P} = \frac{1}{746}\, c\ 2\ a\ b\ m\ Nt\ n\ 10^{-6}.$$

The power to be applied must naturally be somewhat in excess of this in order to overcome mechanical resistances, as friction in the bearings and air resistance, and also the magnetic resistance due to imperfect subdivision of the core, and reaction of the armature on the magnets. In good dynamos these losses amount to about 10 per cent.

CHAPTER III.

Reversibility of Dynamo Machines—Different conditions in Dynamos and Motors—Theory of Motors—Horse-power of Motors—Losses due to Mechanical and Magnetic Friction—Efficiency of Conversion—Electrical Efficiency—Formulas for Dynamos and Motors.

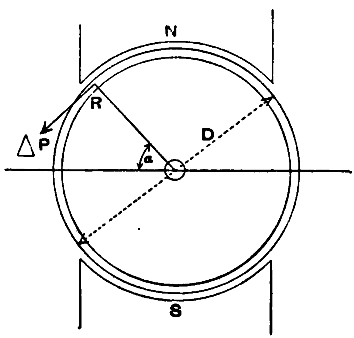
AFTER what has been explained in the previous chapters it will be evident that dynamo machine and electro-motor are convertible terms. Any dynamo can be used practically as a motor, and in most cases any motor can be used to generate a current. On purely theoretical grounds this should be possible in all cases, but in practice it is found that the speed which is required to make some small motors act as self-exciting dynamos is so high as to render that application mechanically impossible. The reason for this is, that in small motors the polar surfaces are of very limited extent, and consequently the magnetic resistance of the path traversed by the lines of force is excessively high, requiring more electrical energy to excite the field magnets than the armature is capable of developing at a moderate and practical speed. This point will be more fully explained further on. For our present purpose it suffices to note that on purely theoretical grounds the same machine can act as a motor or as a dynamo. A separate investigation as to the theory of motors might, therefore, almost seem superfluous. But, on the other hand, experience has shown that although

this reversibility of the dynamo machine exists, it is not always the best dynamo which makes the best motor, and that certain details have to be altered according to the use for which the machine is intended, if we wish to produce the best possible machine for each purpose. The conditions which have to be fulfilled in the case of dynamos are also generally different from those required in motors. The dynamo must have a high efficiency, it must be able to work continuously without undue heating in any of its parts, must not be injured by an occasional excess of current, and must work equally well at extreme variations of electrical output. Its weight is, as a rule, of secondary importance, and in many cases there is no objection to large weights. The motors, on the other hand, are generally required to be of the smallest possible weight, they work intermittently, and high efficiency, although desirable, is not of so much importance, especially not in small motors. In the early days of electric transmission of energy the difference between the conditions in dynamos and motors was overlooked, and the usual arrangement was to employ two identical machines, one acting as generator, the other as receiver, but at the present time this rough-and-ready method does not satisfy all the requirements which can justly be made, and special motors must be provided. It has thus become necessary to study the theory of motors apart from that of dynamos.

Let in Fig. 26, *N S* be the pole pieces and *D* the mean diameter of the annular space filled by the external wires on a cylindrical armature of the Gramme or Hefner-Alteneck pattern. Let, as before, *b* represent the length of the wire and *F* the intensity of the field at a given point *R*, the radius to which forms with the neutral line

the angle α. All the wires on the upper half of the armature will be traversed by currents flowing in the same direction, say from the observer, and all the wires on the lower half will be traversed by currents flowing towards the observer. Let c be the current in each single wire and let there be Nt external wires counted all around the circumference. If these wires lie close together with only as much space between them as is necessary for

Fig. 26.



mutual insulation, the effect of the current c traversing successively the $\frac{Nt}{2}$ wires on one half of the circumference will evidently be the same as that of a semicircular *sheet of current* of total strength $\frac{Nt}{2}$ c, the width of this sheet measured transversely to the direction of flow being $\frac{\pi D}{2}$. The density of current in the sheet, that is, the strength of current per unit of width, is $\frac{Nt}{2} c : \frac{\pi D}{2} = \frac{Nt\ c}{\pi D}$, and the current flowing down an elementary section

at R, the angular width of which ($\Delta\,\alpha$) we take to be very small, is,

$$\Delta\,c = \frac{Nt\,c}{\pi\,D}\frac{D}{2}\,\Delta\,\alpha.$$

The mechanical force tending to rotate the elementary strip of our sheet of current in the direction of the arrow is

$$\Delta\,P = F\,b\,\Delta\,c$$

$$\Delta\,P = F\,b\,\frac{D}{2}\Delta\,\alpha\,\frac{Nt\,c}{\pi\,D}.$$

Now F, the intensity of the field, multiplied with $b\,\frac{D}{2}\,\Delta\,\alpha$, the total area of the elementary strip, gives the number of lines of force which enter the core through that area. Let $\Delta\,Z$ represent that number, and we can also write

$$\Delta\,P = \Delta\,Z\,\frac{Nt\,c}{\pi\,D}.$$

Now consider a second elementary strip of the sheet of current contiguous to the first. The force exerted by this strip will be represented by a similar expression, but in it the value of $\Delta\,Z$ may be different. This will be the case if the field intensity is not uniform, but varies in any way with the angle α. For our purpose it is not necessary to know in what manner the intensity of field F may vary in different points ; whatever the law of variation may be, the sum of all the values of $\Delta\,Z$ must always be the same and equal to the total number of lines passing into the armature core. The mechanical force exerted by the upper semicircular sheet of current, or, which comes to the same thing, by the upper half of the armature winding, $\frac{Nt}{2}$, is therefore

$$Z \frac{Nt\,c}{\pi\,D},$$

Z being the total number of lines. Simultaneously the lower half of the armature exerts the same force, and we have the total force tending to rotate the armature, and acting at a radius equal to that of the winding, $\frac{D}{2}$,

$$P = \frac{2\,Z\,Nt\,c}{\pi\,D}.$$

The turning moment, or torque, is $P\frac{D}{2}$, or

$$T = \frac{Z\,Nt\,c}{\pi}, \quad \ldots\ldots\ldots \; 7).$$

If we express the total number of lines by the product of their density within the armature core and the dimensions of the latter, we can also write for the torque

$$T = \frac{2\,a\,b\,m\,Nt\,c}{\pi} \ldots\ldots\ldots \; 8).$$

It has already been mentioned that there exists a limit beyond which m cannot be increased, however powerful the field magnets may be. Assume that in two motors of different size the field magnets are excited so as to produce equal and maximum density of lines in both armature cores, and assume also that both armatures are wound with wire of the same gauge, then the number of turns will in the larger machine be greater than in the smaller, the proportion being evidently as the squares of their linear dimensions. Since the areas of the cores are also in the same proportion, it follows that the torques or turning moments are in the proportion of the fourth power of the linear dimensions. Thus, if the larger motor be double the linear dimensions of the smaller, its

torque will be sixteen times as great. It will be seen from formula 7, that the torque of a motor depends only on the strength of the field and on the current, but does not depend on the speed. This can be shown experimentally in the following manner. Let two series-wound dynamos be connected by a pair of cables, and let one of these act as generator, whilst the other, which is the motor, is provided with a friction brake, on which the energy given out can be measured. Whatever the speed of the motor may be, the brake, if its lever be floating free, indicates the turning moment in the shaft of the motor. This turning moment is equal to the product of the length of the lever and the load suspended. If now the speed of the generator be varied so as to vary the electro-motive force, the speed of the motor will accordingly vary, but the current and the load on the brake will remain unaltered. In dealing with this matter, M. Marcel Deprez, in "La Lumière Electrique" of the 3rd of October, 1885, says:—"If a current traverses a motor having an armature of the Pacinotti type, the turning effort of the latter is independent of its state of movement or rest, and in motion it is independent of the speed, provided the strength of the current is maintained constant. Inversely, if the static moment tending to resist the motion of the armature is maintained constant, the current will thereby automatically be kept constant, whatever means we may employ to vary it. The experiment must be made in the following way. Mount upon the spindle of the motor a self-adjusting dynamometric brake, the load on which is automatically kept constant whatever variation may take place in the friction of the brake or in the speed of the motor, so that the tangential resistance which tends to oppose rotation shall be kept

constant. Supply the motor with current from any given source of electricity (a battery or a dynamo machine), and note the strength of the current and its electro-motive force. If the latter be gradually increased from zero we observe that as long as the motor remains at rest the current grows in the same proportion, but as soon as it has reached a certain value and the motor has begun to turn, the current does not further increase, although the rise in the electro-motive force may continue, and with it the rise in the speed of the motor. In an experiment made three years ago the source of electricity was a Gramme dynamo and the motor a Hefner-Alteneck machine, the brake being loaded with $5\frac{1}{2}$ lbs. at a radius of $6\frac{3}{8}$ inches. When the motor began to turn, the needle of the ampere-meter indicated twenty-six divisions. I then augmented the speed of the dynamo until the motor made thirty-two revolutions per second, and yet the ampere-meter only indicated twenty-seven divisions instead of twenty-six."

Since with a constant load on the brake, the energy given out is proportional to the speed, and since the electrical energy supplied to the motor is the product of current and electro-motive force, it follows that if the current is constant the speed must be proportional to the electro-motive force. The following table taken from M. Marcel Deprez's article shows that this is indeed the case. It will be seen that in all the four motors tested the ratio of electro-motive force to speed remained nearly constant throughout a very wide range of speed, and that the current also remained practically constant.

Type of motor.	Revolutions per minute.	Current.	Electro-motive force. / Speed.
Hefner-Alteneck .	425	13·53	·0267
	783	12·68	·0262
	1165	13·65	·0278
	1660	13·00	·0250
A Gramme . . .	270	8·16	·06496
	526	8·16	·06437
	608	8·23	·06768
	742	8·40	·06792
	944	8·23	·06713
	1004	8·23	·06803
	1160	8·23	·06704
	1460	8·23	·06736
Hefner-Alteneck .	356	5·60	·0132
	618	5·78	·0139
	1016	5·42	·0127
	1236	5·60	·0130
	1470	5·95	·0129
	1636	5·60	·0127
	1662	5·42	·0127
High tension machine	200	5·60	1·659
	384	6·30	1·692
	470	6·12	1·775
	606	5·95	1·633
	710	5·95	1·662

Going now back to equation 7), the mechanical energy represented by one revolution of the motor shaft is evidently $2\,\pi\,T$, and if the motor runs at a speed of n revolutions a minute, or $\frac{n}{60}$ revolutions a second, the energy developed during that time is

$$W = Z\,Nt\,2c\,\frac{n}{60} \quad \ldots\ldots\ldots \quad 9).$$

It will be remembered that each half of the armature carries the current c; $2c$ is consequently the total current passing into the armature at one brush and out at the other. Write Ca (armature current) for $2c$ and we have

$$W = Z\,Nt\,\frac{n}{60}\,Ca \;.\;.\;.\;.\;.\;.\;.\;.\;. \quad 10).$$

But from equation 4) we found that the counter electromotive force of the armature is

$$Ea = Z\,Nt\,\frac{n}{60} \;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;. \quad 4),$$

and combining the two equations we find

$$W = Ea\,Ca \;.\;.\;.\;.\;.\;.\;.\;.\;. \quad 11).$$

The mechanical energy equals the product of current and electro-motive force, that is, equals the electrical energy. This, indeed, is self-evident from the principle of the conservation of energy; and starting with the equations 4) and 11), we could have deduced the expressions for W and T from these. But on the other hand it is more satisfactory to have determined these values independently, and to find that our conclusions are verified by the principle of the conservation of energy.

All the equations above are based on the absolute system of measurement. For practical purposes, however, the employment of these units is not convenient, and instead of using dynes or ergs we prefer to make our calculation in pounds and horse-powers. It will therefore be necessary to determine the relation between the absolute and practical units.

According to the definition of the dyne given in the first chapter, it is that force which accelerates the mass of one gram by one centimeter in one second. It would

not be strictly correct to represent the dyne as equal to a certain fraction of a kilogram or of a pound, because the value of unit mass (that of one gram) changes according to the position on the surface of the earth where we may happen to measure it. But in all places the following equations hold good :—

$$P = m\,v,$$
$$G = m\,g.$$

P being the force to which corresponds the acceleration v, G being the weight of the body measured by the acceleration of gravity g, and m being the mass of the body

$$P = G\,\frac{v}{g}.$$

If g be given in meters per second and the weight in kilograms, the force of one dyne is,

$$\text{Dyne} = \frac{10^{-3}\,10^{-2}}{g}\ \ldots\ldots\ \text{kilograms.}$$

$$\text{Dyne} = \frac{10^{-5}}{g}\ \ldots\ldots\ldots\ \text{kilograms.}$$

The energy represented by one dyne acting through the distance of one centimeter, the erg, is therefore

$$\frac{10^{-5}}{g}\ \ldots\ \text{kilogram-centimeters, or,}$$

$$\text{Erg} = \frac{10^{-7}}{g}\ \ldots\ \text{kilogram-meters.}$$

According to equation 11) the number of ergs developed by the armature of the motor is numerically equal to the product of current and electro-motive force in absolute measure. If we wish to insert these values expressed in practical units of amperes and vults we have

$$W = 10^{-8} \times 10^{+1}\ \ldots\ \text{voltamperes,}$$
$$W = 10^{-7}\ \ldots\ldots\ \text{watts.}$$

To obtain the number of watts represented by a certain number of ergs, we have therefore to multiply the latter by 10^{-7}. Similarly to obtain the number of kilogram-meters represented by a certain number of ergs, we have to multiply the latter by $\frac{10^{-7}}{g}$,

$$\text{Watts} = 10^{-7} \times \text{ergs},$$

$$\text{Kilogram-meters} = \frac{10^{-7}}{g} \times \text{ergs}.$$

From these two equations we find that

$$\text{Kilogram-meters} = \frac{\text{Watts}}{g}.$$

The energy required to lift 75 kilograms one meter high in one second is a standard horse-power. The acceleration of gravity may be taken as 9·81 meters per second, hence one horse-power is represented by

$75 \times 9{\cdot}81$ . . . watts, or in round numbers:

736 *watts correspond to one standard horse-power.*

In English measure the standard horse-power is equal to 32,500 foot pounds work done per minute. The usual English horse-power is equal to 33,000 foot pounds. Hence, to obtain the number of watts representing an English horse-power, we must multiply 736 with the ratio of 33,000 to 32,500. This gives the figure 746. Let Ea represent the counter-electro-motive force of the armature in volts, and Ca the current in amperes, then the number of English horse-powers which could be obtained from it, if there were no losses, is

$$H\text{-}P = \frac{Ea\ Ca}{746} \quad \ldots\ldots\ldots\ldots \quad 12).$$

Retaining the notation of equations 5) and 6), we have also

$$H\text{-}P = \frac{1}{746} Z\ Nt\ n\ 10^{-6}\ Ca \ \ldots\ldots\ 13),$$

$$H\text{-}P = \frac{1}{746} 2\ a\ b\ m\ Nt\ n\ 10^{-6}\ Ca\ \ldots\ 14).$$

The power which is actually obtainable is somewhat smaller, as certain losses occur. These might be classified under two headings, mechanical friction and magnetic friction. The former consists of the friction in the journals, of that between the commutator and the brushes, and of the resistance which the air offers to the rapid rotation of the armature, or the "windage," as it is technically termed. The latter is of a somewhat complicated nature, and may manifest itself in various ways, but more especially in the heating of the armature core and of the pole pieces. If the armature core is not sufficiently subdivided, a fault very common in small motors, currents will be generated in it, which will be the stronger the more intense the field and the quicker the speed. It is as though the motor contained a dynamo working on short circuit, and the power necessary for producing these currents must be supplied by the current flowing through the coils of the armature, and represents therefore so much power withdrawn from external use. Another source of loss is the limited number of the sections in the commutator. In establishing our formulas we have assumed that the aggregate of the currents in the different wires can be represented by a continuous semicircular sheet of current. This assumption is, strictly speaking, only correct if the number of wires and the corresponding number of sections is infinite. But when these numbers are limited, and especially when one section of the commutator corresponds to a wide coil,

consisting of a great many turns of wire on the armature, then the change of contact between the brushes and successive commutator strips produces abrupt changes in the magnetizing effect of the current on the core of the armature, and our sheet of current, instead of being fixed in space as first assumed, undergoes violent oscillations, the amplitude of which is equal to the angular distance between two neighbouring coils. It is as though a magnet placed at right angles to the centre line through the pole pieces were kept in rapid oscillation, and since any magnet, if moved in the neighbourhood of metallic masses will heat the latter and absorb power, it follows that the pole pieces will become hot, and part of the energy produced by the motor will be wasted in this way. From what has just been explained, it will be evident that this loss can be reduced by increasing the number of sections in the commutator, and by subdividing the metal of the pole pieces by planes at right angles to the axis of the armature.

Another source of loss in some motors is the discontinuity of the armature core. This loss does not occur in Gramme armatures with smooth cylindrical cores; but in armatures of the Pacinotti type, the projecting teeth, in sweeping closely by the polar surfaces, react on the latter, and produce eddy currents therein, which in their turn exert a retarding force upon the teeth. That this is really the case is shown in a striking manner in many dynamos having Pacinotti projections, notably in the Brush and Weston machines. Everyone who has examined these machines after some hours' work, must have noticed that the pole pieces, especially where the coils and projections leave them, grow hot. At the entering side the heating is not so great, because there

the magnetizing effect of the armature current is to repel and weaken the lines, whereas at the leaving side it is to attract and strengthen them. If the machines be used as motors an opposite effect is produced, the pole pieces becoming hottest at the entering side. Cores with Pacinotti projections are very much in favour with the designers of motors, because it is thought that they increase the magnetic attraction which determines the force of the motor. On purely theoretical grounds this is so. It will be shown presently that the number of lines Z, passing from the pole piece to the armature is the greater, the smaller the distance they have to leap through air, and by allowing the teeth to project so far as to almost touch the polar surfaces, the magnetic resistance of the air space can be very considerably reduced. But in practice such perfection is unattainable on account of heating and waste of power just explained. It is found necessary to make the clearance between the outer surface of the teeth and the inner surface of the pole pieces much greater than would suffice for free rotation, and it may be doubted whether the Pacinotti core is, after all, so great an improvement over the Gramme core as on purely theoretical grounds it seems to be.

In good motors the sum total of all the losses here enumerated at length amounts to only a small fraction of the total power. The ratio between that and the power actually obtainable on the shaft is called the *efficiency of conversion*, and it should never be less than 90 per cent. in medium-sized and large motors.

The *electrical efficiency* of the motor is the ratio of total internal electrical horse-power, as given by our formulas 13) and 14), to the external electrical horse-power applied at the terminals of the motor. Let

E_a represent the electro-motive force created in the armature coils.

E_b represent the electro-motive force appearing at the brushes.

E_t represent the electro-motive force appearing at the terminals.

r_a represent the total resistance of the armature.

r_m represent the total resistance of main coils on field magnets.

r_s represent the total resistance of shunt coils on field magnets.

C, C_a, C_s, C_m represent the external current, the current through the armature, through the shunt coils and main coils on field magnets respectively. Then for a compound-wound dynamo the following equations evidently obtain:

$$C = C_m, C_s = \frac{E_b}{r_s}$$

$$C_a = C_m + C_s \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 15),$$

$$E_b = E_a - r_a \, C_a \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 16),$$

$$E_t = E_b - r_m \, C_m \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 17).$$

The electrical efficiency is

$$\eta = \frac{E_t \, C}{E_a \, C_a} \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 18).$$

For an electro-motor, also compound-wound, the equations are

$$C = C_m, \; C_s = \frac{E_b}{r_s},$$

$$C_a = C_m - C_s \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 19),$$

$$E_b = E_t - r_m \, C_m \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 20),$$

$$E_a = E_b - r_a \, C_a \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 21),$$

$$\eta = \frac{E_a C_a}{E_t \, C} \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 22).$$

We assume hereby that both in the motor and dynamo the shunt coils be coupled direct to the brushes. If they are coupled to the terminals the formulas are for the dynamo,

$$C = C_m - C_s,\ C_s = \frac{E_t}{r_s},\ C_a = C_m,$$

16), 17), and 18) remaining unaltered.

For the motor we have

$$C_m = C - C_s,\ C_s = \frac{E_t}{r_s},\ C_a = C_m,$$

20), 21), and 22) remaining unaltered.

The same formulas are applicable to the case of plain series or shunt machines, whether dynamos or motors, but in the case of series machines we insert $r_s = \infty$, and in the case of shunt machines we insert $r_m = o$.

CHAPTER IV.

Types of Field Magnets—Types of Armatures—Exciting Power—Magnetic Circuit—Magnetic Resistance—Formulas for strength of Field—Single and Double Magnets—Difficulty in Small Dynamos—Characteristic Curves—Horse-power Curves—Speed Characteristics—Application to Electric Tramcars—Static, Dynamic, and Counter-Electro-motive Force.

In the preceding chapter it has been shown how the electro-motive force of an armature can be found if the total number of lines passing through its core be known. It will now be necessary to determine the number of lines, that is the strength of the magnetic field, from the constructive data of the machine. Before entering into a scientific investigation of the subject a cursory glance at the different types of field magnets adopted by the various makers of dynamos and motors, will be of interest. These are shown in Figs. 27 to 51. To make the classification comprehensive the type of armature is written beneath each field and the maker's or designer's name is written above it. We distinguish three types of armature. 1. *The Drum,* wound on the Hefner-Alteneck principle, as explained in Chapter II., and shown in Figs. 18 and 19; 2. *The Cylinder,* wound on the Pacinotti or Gramme principle, also explained in Chapter II., and shown in Figs. 25 and 20; and 3. *The Disc,* wound on the Pacinotti or Gramme principle and only differing from the cylinder by the shape of the core. It is a cylinder of considerable diameter and small length, in fact a flat ring or disc.

All the magnets employed in dynamos or motors are horse-shoes ; straight-bar magnets with poles at the ends being never used. The reason is obvious. We must in all cases bring opposite poles to the same armature, and that necessitates the employment of a bent magnet. It is necessary to distinguish between single, double, and multiple magnets. In the single horse-shoe magnet all the lines passing across the armature go through the magnet in the same direction. As an example we may take the Edison-Hopkinson dynamo, Fig. 27. The lines passing across the armature from *N* to *S* continue all in the same direction, viz., vertically upwards from *S* to *B*, thence across the yoke from *B* to *A*, and finally vertically, downwards from *A* to *N*. A free unit pole would be urged along the closed magnetic circuit *N S B A N*, and there is no other way along which it could travel. Now in a double horse-shoe, as represented for instance by the Weston machine, Fig. 41, there are two ways along which a unit pole might travel. One of these is *N S B A N*, and the other *N S D C N*, or in other words, of the total number of lines passing across the armature, one half will go through the horse-shoe *N A B S*, and the other half will go through the horse-shoe *N C D S*. We may consider the field magnets to consist of these two horse-shoes placed with like poles in contact to the left and right of the vertical center line. The arrangement of the "Manchester" dynamo is similar, but in this case the portions *A B* and *C D*, which in the Weston dynamo constitute the yokes, form the excited or active parts of the magnets and are surrounded by the magnetizing coils. The field magnets of the original Gramme dynamo (or motor) also belong to the double horse-shoe pattern. But in this case a plane laid through the center lines of the cores of the

magnets is parallel to and contains the center line of armature shaft, whereas in the Weston type it is at right angles to it. Here, again, the lines are split up to the right and left of the vertical center line into two distinct circuits. Fig. 37 shows a similar arrangement, but with a single magnet. Figs. 39, 40, and 50 show single magnets, the plane of the horse-shoe being at right angles to the armature. Fig. 48 shows a quadruple horse-shoe magnet. Here the lines of force passing across the armature belong to four distinct circuits: *S D A N*, *S D C N*, *S B A N*, and *S B C N*. The field magnets of the Brush (Victoria) machine shown in Figs. 46 and 47 consist of 8 complete horse-shoes, four on each side of the disc, and in some multipolar machines even a larger number of magnetic circuits is sometimes employed. The latest machines of M. Marcel Deprez (Fig. 51) have two cylinder armatures mounted on the same spindle *a b*, and around them are placed eight horse-shoes, of which two, *S B A N* and *S C D N*, are shown in the illustration. It is not necessary to enter into a detailed description of all the types shown, as the diagrams are alone sufficiently clear.

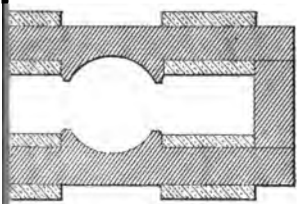
After what has been said above it will be evident that the proper function of the field magnets in a dynamo or motor is to produce lines of force which pass across the armature core. All other lines which miss the armature are useless and may even be detrimental to the working of the machine. The greater the number of useful lines the greater will be the electro-motive force generated at a given speed and with a given armature. Our aim should therefore be to produce a maximum number of lines, and as a first step towards the realization of this object we must determine the relation between the number

of lines and the constructive data of the machine. of these data is the exciting power, that is the prod the number of turns of wire wound on the magn the magnetizing current sent through the wire. customary to reckon the exciting power in *Ampere-* and it is shown by experiment and theory that the in which the product is made up is quite imma We may have a large number of turns of fine wire small current, or we may have few turns of stou and a large current. The effect will always be th if the product of amperes and turns be the same. periment also shows that for low degrees of magneti the electro-motive force produced in the armature portional, or nearly so, to the exciting power P a to the field magnets ; and since electro-motive for strength of field Z are always proportional, we fin in these cases Z is proportional to P. We can rep this relation mathematically by introducing the conc of *magnetic resistance.* According to this there every magnetic circuit a passive force opposing the tion of lines, and the number of lines which are nev less created is the quotient of the magnetizing for this resistance. Calling the latter R, we have

$$Z = \frac{P}{R}. \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; .$$

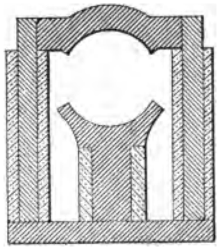
This formula is rigorously correct, provided we s in determining the magnetic resistance for every con of magnetization. For low degrees of magnetizati resistance is nearly constant, and in these cases exists simple proportionality between Z and P ; for degrees of magnetization the resistance increases a relation between Z and P becomes more compl A limit is ultimately approached beyond whi

Fig. 33.
PATERSON AND COOPER.



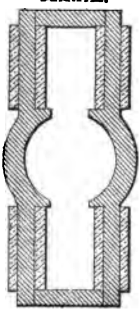
SHORT CYLINDER.

Fig. 34.
GOOLDEN AND TROTTER.



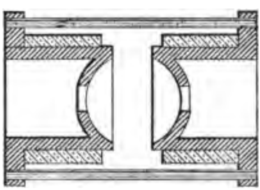
SHORT CYLINDER.

Fig. 42.
MAXIM.



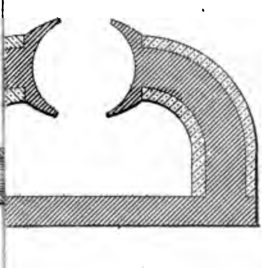
CYLINDER.

Fig. 43.
THOMSON-HOUSTON.



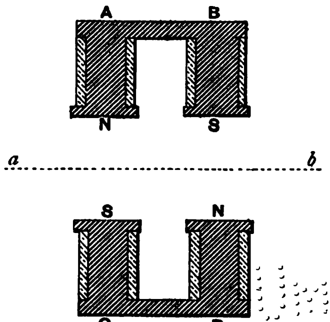
SPHERE.

Fig. 50.
JÜRGENSEN.



CYLINDER.

Fig. 51.
MARCEL-DEPREZ.



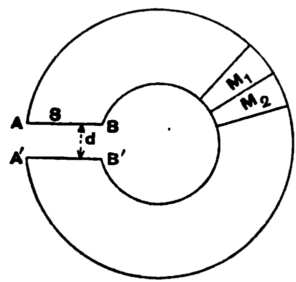
TWO CYLINDERS.

To face page 10

cannot increase the strength of the field although we may increase the exciting power indefinitely. In this case the magnetic resistance has become infinite, and this condition is generally expressed by saying the magnet is *saturated.* The relation existing between magnetizing power and the magnetic moment have in the case of straight-bar magnets, spheres, and ellipsoids been investigated by Jacobi, Dub, Müller, and others, and a variety of formulas have been proposed to express these relations mathematically. Apart from the fact that these formulas in themselves are only rough approximations but imperfectly fitting the results of experiments, they are for practical purposes almost useless, since the field magnets of dynamos and motors are not straight bar magnets, but horse-shoes of every possible form and variety. In some cases these formulas are even misleading, and as an example we may cite the original Edison machines. According to the orthodox theory the magnetic moment of a cylindrical bar is proportional to some function of the exciting power, to the square root of the diameter of the bar and to the square root of the cube of its length. Hence to obtain a maximum of magnetic moment with a given weight of iron we must shape it into a long cylinder, and the original Edison machines were constructed on these lines. Experience has since then taught us that this was the worst possible form which could have been adopted, and the Edison machines built subsequently have stout and short magnets. The explanation for this apparent discrepancy between theory and practice is this, that in a dynamo or motor the magnetic moment of each bar composing the field magnet is of no account whatever, the electro-motive force depending only on the total number of lines produced, which is governed by laws

totally different from those relating to the magnetic moment. It is very desirable that the relations between strength of field and exciting power should be mathematically established for those forms of magnets which are actually used in the construction of dynamos and motors. As yet no formula rigorously true for all degrees of magnetization has been found, and the difficulty is principally due to the fact that the chemical composition and molecular properties of the iron play an important part which is not easily determinable beforehand. This

Fig. 52.



is especially the case if the magnetization is pushed towards the saturation limit. For lower degrees of magnetization the difficulties are still present, but they are of relatively less importance, and it is possible to establish formulas for the strength of the field which are sufficiently approximate for practical purposes.

Let in Fig. 52 a series of wedge-shaped and very short magnets, M_1 M_2 . . . be placed with polar faces of opposite sign in contact, so as to form a continuous ring interrupted only by the air space A B, A^1 B^1. Lines of force will then pass across this air space, and an electro-motive force could be created by moving a conductor or series of

conductors, so as to cut these lines. Let the polar surface of each elementary magnet be S, and let the density of magnetic matter, which we imagine to be distributed over the polar surfaces, be σ, then $\sigma\ S$ is the strength of each polar surface. According to Ampere's theory each elementary magnet can be replaced by an equivalent magnetic shell (page 27), consisting of a closed conductor in which a current flows, the product of current and area enclosed being numerically equal to the magnetic moment of the elementary magnet. Imagine now the magnets replaced by a spiral of wire or *solenoid*, then we can without appreciable error consider each turn of wire in the spiral as a current closed in itself, and if there be n such turns, and if the current be C, the total magnetic moment will be in absolute measure $n\ C\ S$. Since with the exception of the two end faces $A\ B$, $A^1\ B^1$, the polar sufaces are in contact and cannot exert any action at a distance, the total magnetic moment of the series of elementary magnets is represented by the product of the magnetism on the end faces, and their distance, d. We have therefore the equation,

$$\sigma\ S\ d = n\ C\ S.$$

It has been shown (page 24), that the total number of lines emanating from unit pole is $4\ \pi$. From a pole of the strength $\sigma\ S$ there must emanate $4\ \pi\ \sigma\ S$ lines. Let Z be the total number of lines, or strength of field within the air space, then we find

$$Z = 4\ \pi\ \sigma\ S,$$

and by inserting the value of $\sigma\ S$ from above equation,

$$Z = \frac{4\ \pi\ n\ C\ S}{d},$$

which can also be written in the form

$$Z = 4\pi \frac{n\,C}{\frac{d}{S}}$$

The product $n\ C$ is exciting power in absolute measure, or ampere turns $\times\ 10^{-1}$. S is the polar surface, and d the distance between the two poles. In deducing the formula for Z we have assumed the polar surfaces to be two parallel planes, but it can be proved that the same law holds good for surfaces of any shape, provided that their distance is very small as compared to their area. We can therefore apply the formula to the case of a cylindrical polar cavity partly filled by a cylindrical armature. Here we have two air spaces, and the polar surface S is the product of length of armature, b and the arc spanned by either pole, λ. Let δ be the distance between the polar surface of the magnets and the external surface of the armature core, and let P represent the exciting power producing Z lines, then the above formula becomes

$$Z = 4\pi \frac{P}{\frac{2\,\delta}{\lambda\,b}}$$

$$Z = \frac{P}{\frac{2\,\delta}{4\,\pi\,\lambda\,b}} \quad \ldots\ldots\ldots\ldots \quad 24).$$

The strength of the field is represented by the quotient of exciting power, and an expression which is of the character length divided by area. The analogy with Ohm's law will be apparent. The electrical resistance of a conductor is found by multiplying its specific electrical resistance with the length, and dividing by the area of the wire. In the same manner the magnetic

resistance of the air space is found by multiplying $\frac{1}{4\pi}$ with the length (2δ), and dividing by the area (λb) of the air space. We can therefore regard $\frac{1}{4\pi}$ as the specific magnetic resistance of air. The expression 24) gives the field in absolute lines; to obtain it in such measure as to be directly applicable for the determination of electro-motive force by equation 5) we must divide by 6,000. If for convenience we also use inches instead of centimeters in the dimensions δ, λ and b and Ampere turns, instead of exciting power in absolute measure we find

$$Z = \frac{P}{1875 \frac{2\delta}{\lambda b}}.$$

This formula is only correct under two suppositions. First, that there shall be no other resistance in the magnetic circuit but that of the air space, and secondly that the iron contained within the coils of the solenoid does not in any way contribute to the creation of lines. But we know that the presence of iron in a coil has the result of increasing the number of lines created by the coil *per se*, and that the ratio of this increase depends on the quality of the iron. We must therefore expect that the figure in the denominator of the above expression will in reality be somewhat less than 1875. From a large number of experiments made by the author with dynamos of various sizes and types, it was found that the resistance of air space can be represented by

$$1440 \frac{2\delta}{\lambda b},$$

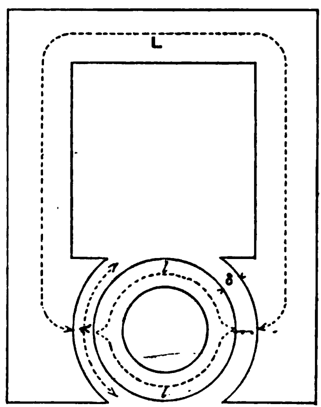
if the field magnets and armature core consist of well annealed wrought iron, and by

$$1800 \frac{2\,\delta}{\lambda\, b},$$

if the field magnets be of cast iron and the armature core of wrought iron.

The resistance of air space is, however, not the only passive force which opposes the creation of lines. There is also the resistance of the field magnet itself and that

Fig. 53.



of the armature. It is reasonable to suppose that these resistances are also of the character: length divided by area, the fraction being multiplied with a coefficient depending on the quality of the iron. Let in Fig. 53, *L* represent the average length of the magnetic circuit within the field magnet, and *A B* the cross-sectional area of the magnet core. Let, in the same manner, *l* represent the average length of the magnetic circuit within the core of the armature, which we suppose to be

of the cylindrical Gramme type, and $a\,b$ the area of the core. The magnetic resistance of the single horse-shoe magnet will then be proportional to $\frac{L}{A\,B}$, and that of the armature to $\frac{l}{2\,a\,b}$, each of these fractions being multiplied by a coefficient depending on the quality of the iron. From numerous experiments the author has found that for dynamos and motors of this type made of well annealed wrought iron, the strength of the field for low degrees of magnetization is represented by the expression,

$$Z = \frac{P}{1440 \frac{2\,\delta}{\lambda\,b} + \frac{l}{a\,b} + \frac{2\,L}{A\,B}} \quad \ldots\ldots \quad 25).$$

For cast-iron magnets the formula is

$$Z = \frac{0{\cdot}8\,P}{1800 \frac{2\,\delta}{\lambda\,b} + \frac{l}{a\,b} + \frac{3\,L}{A\,B}} \quad \ldots\ldots \quad 26).$$

In the case of double horse-shoe magnets, as shown in Fig. 54, each horse-shoe contributes half the total number of lines, and we have for wrought iron,

$$\frac{Z}{2} = \frac{P}{1440 \frac{2\,\delta}{\lambda\,b} + \frac{2\,l}{a\,b} + \frac{2\,L}{A\,B}} \quad \ldots\ldots \quad 27),$$

and for cast-iron

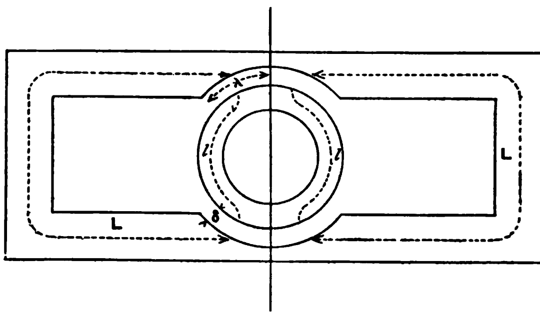
$$\frac{Z}{2} = \frac{0{\cdot}8\,P}{1800 \frac{2\,\delta}{\lambda\,b} + \frac{2\,l}{a\,b} + \frac{3\,L}{A\,B}} \quad \ldots\ldots \quad 28).$$

The exciting power required to produce a certain strength of field can be found by multiplying the number of lines with the magnetic resistance, as represented by the denominator in the above four equations. It should be remembered that these only apply to cases where the

intensity of magnetization is not too great, say up to ten lines per square inch. For more intense fields the magnetic resistance of the iron part of the circuit increases considerably, and in practice it is found that to bring the field magnets of dynamos or motors near to saturation from 40 to 100 per cent. more exciting power must be applied than given by the above formulas.

A question of great practical importance is the relative advantages of the single and double magnet. Since in the latter the area of air space is only half that of the

Fig. 54.



former, the resistance of air space is doubled. On comparing equations 25) and 27), it will be seen that the magnetic resistance of the magnet is equal in both cases, and that the magnetic resistance of armature and air in the double horse-shoe is about double that of the single horse-shoe. On the other hand, only half the total number of lines have to pass through one magnet of the double horse-shoe type, and therefore the exciting power in the single and double magnet is about the same. But in the latter case this exciting power has to be applied on each of the two horse-shoes, whereas in the

single-magnet machine it has to be applied on one horseshoe only, but of double the sectional area. The length of wire required will therefore be as $2 : \sqrt{2}$, or by the single magnet system a saving of about 25 per cent. of wire can be effected. On the other hand, the iron portion of the single magnet is somewhat heavier than that of an equivalent double magnet, and in cases where smallness of total weight is a consideration, as for instance in motors used for locomotive purposes, the double magnet, notwithstanding that it requires more wire, has a distinct advantage.

An inspection of formulas 25) to 28) will show why, as was already mentioned in the beginning of Chapter III., small motors sometimes fail to act as dynamos. In these machines, or to speak more correctly, in these models of machines, the polar surfaces $\lambda\, b$ are very small as compared to the air space δ, and consequently the magnetic resistance of air space is very high. The exciting power is therefore also very high as compared to the strength of field, and it may happen that the electrical energy which is required to produce so large an exciting power is greater than the total electrical energy which can possibly be produced by the armature. In this case the machine fails to act as a dynamo.

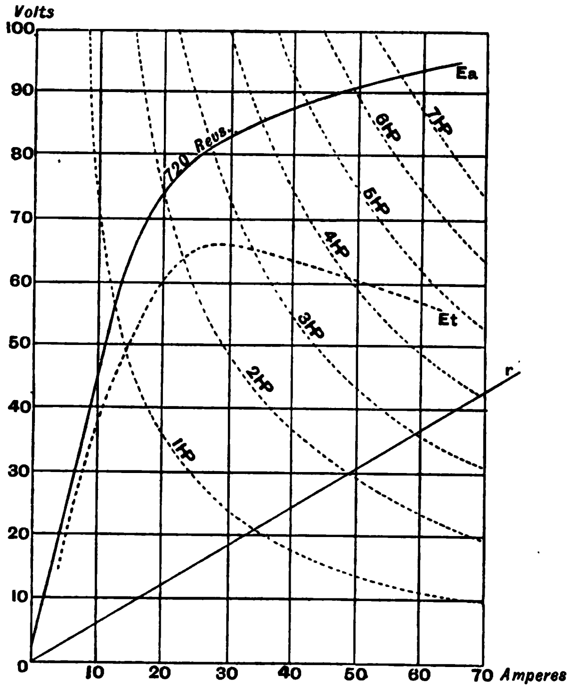
Since the electro-motive force for a given speed of rotation is proportional to the strength of the field, and since that depends in its turn on the exciting power, it follows that in every dynamo or motor there exists a definite relation between the electro-motive force created in the coils of the armature and the ampere turns applied to the field magnets. As already stated, this relation is of too complicated a nature to permit of its being represented in the form of a mathematical expression rigo-

rously applicable to all cases. Approximate formulas have been devised by Fröhlich, Clausius and others, but these are not sufficiently accurate for practical use, and have moreover the disadvantage common to all analytical methods of not appealing directly to our senses. In this respect graphic methods are much more preferable, and in the solutions of problems connected with dynamos and motors they offer facilities far beyond those of any analytical treatment. It is possible to represent all the important properties of a machine by curves, and since these properties give it a distinct character by which it differs from other machines of similar type, these curves are called *characteristics*.[1] The relations between current, electro-motive force, speed, horse-power, efficiency, and so forth, can all be represented graphically, but the curve most commonly used is that giving the electro-motive force as a function of the exciting power for a constant speed. In the case of a series dynamo the exciting power is proportional to the current, and if we plot the currents on the horizontal and the corresponding electro-motive forces created in the armature coils on the vertical, we obtain what is commonly known as the *internal characteristic*. The *external characteristic* is a curve representing the electro-motive force at the terminals of the dynamo, and the distance between corresponding points on the two curves represents the loss of electro-motive force occasioned by the internal resistance of the machine. Fig. 55 shows the internal and external characteristics of a series-wound Siemens dynamo as given by Dr. Hopkinson in his paper reprinted in the

[1] This name appears to have been first used by M. Marcel Deprez, in 1881, in an article in "La Lumière Electrique," although Dr. Hopkinson was the first to make use of graphic methods as applied to dynamos.

Proceedings of the Institution of Mechanical Engineers, 1879. The dotted curve $O\ E_t$ represents the electromotive force at the terminals of the machine, and the curve shown in a full line $O\ E_a$, that in the armature.

Fig. 55.



CHARACTERISTICS OF SIEMENS DYNAMO.

The latter is obtained from the former by adding to its ordinates the internal loss of electro-motive force. This is the product of current and internal resistance, which latter was in that particular machine 0·6 ohms. Thus at 50 amperes the loss is 30 volts, and it will be

seen from the diagram that the difference between the two ordinates corresponding to 50 on the abscissæ is 30. We can also represent the loss of electro-motive force by a characteristic, and since it is always proportional to the current, the characteristic in this instance becomes a straight line, $O\ r$. The geometrical tangent of the angle which this line forms with the horizontal is evidently equal to the internal resistance of the machine. The ordinates enclosed between $O\ r$ and $O\ E_a$ represent the external electro-motive forces, and therefore the internal characteristic, $O\ E_a$, becomes the external characteristic if we take $O\ r$ for the base line instead of the horizontal.

By a very ingenious method due to Professor Silvanus P. Thompson these characteristics can also be used to show at a glance the horse-power which corresponds to any particular current or electro-motive force. As already shown the horse-power represented by a current c flowing under an electro-motive force E_a is H-P $= \frac{c\ E_a}{746}$. One horse-power can be represented by an infinite variety of c and E_a, but these values must all satisfy the equation

$$746 = c\ E_a.$$

A curve representing one horse-power will pass through all such points of which the product of their ordinates is a constant, viz., 746. Similarly a curve representing the value of two horse-power will pass through points of which the product of their ordinates equals 1492, and so on. In other words, all the horse-power curves are rectangular hyperbolas,[1] and by drawing a set of these curves across our diagram—as shown in dotted lines—we can

[1] The scales for volts and ampères being equal.

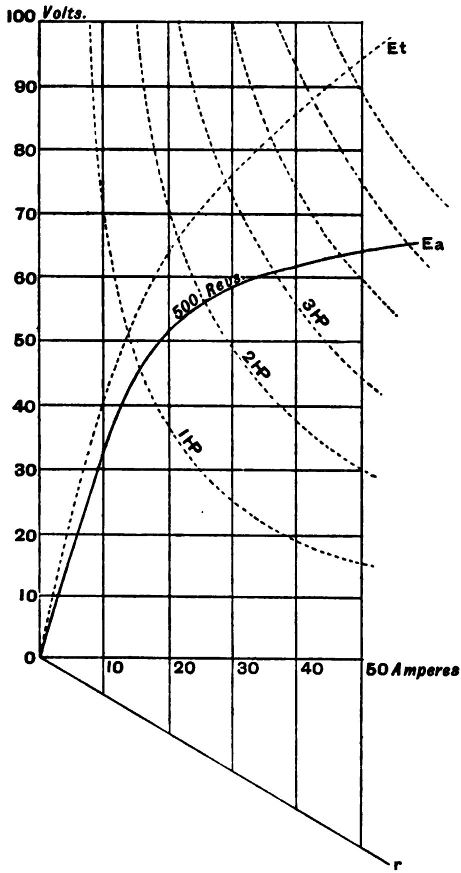
determine at a glance what is the horse-power corresponding to any point on the characteristic. Thus a current of 30 amperes represents about 3·35 H-P of internal electrical energy, and about 2·7 H-P of electrical output or energy delivered into the external circuit. A current of 50 amperes represents a little over 6 H-P internal, and a little over 4 H-P external energy, and so on.

In a dynamo the internal characteristic lies always above the external characteristic. In a motor, however, their position is reversed, since the external electro-motive force must necessarily be greater than the counter-electromotive force developed in the armature coils. Fig. 56 shows the characteristics of the Siemens dynamo mentioned above if used as motor. Not to get the diagram too long the speed has been reduced to 500 Revolutions. The curve $O\ E_a$ represents the counter electro-motive force developed in the armature coils, and the curve $O\ E_t$, which is shown in a dotted line, represents the terminal electro-motive force. The difference between the ordinates of the two curves represents the electro-motive force necessary to overcome the internal resistance of the machine. By drawing the straight line $O\ r$ under an angle, the tangent of which is numerically equal to the internal resistance, but this time below the horizontal and not above it as in the former example, we can regard it as the new base line, and then the curve $O\ E_a$ becomes the external characteristic.

In diagram (Fig. 56) it is assumed that by some means we keep the speed constantly at 500 revs. a minute. Easy as it is to fulfil such a condition in a dynamo, it presents considerable difficulties if we have to deal with a series-wound motor, because its speed depends on a number of factors which to a certain extent may vary independently

of each other. The speed depends on the current and

Fig. 56.



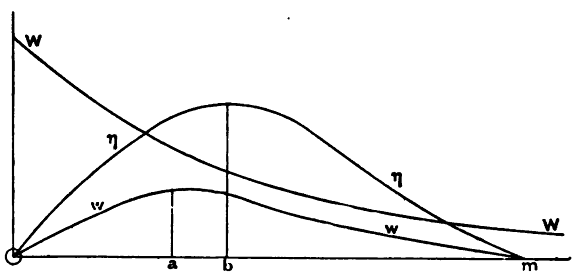
CHARACTERISTICS OF SERIES MOTOR.

electro-motive force supplied to the motor, and on the amount of mechanical work it has to do. In some cases

the work itself, that is the product of turning moment and speed, depends on the latter, and thus it will be seen that the relation between these various quantities is of a rather complex nature. It is however easy to represent these relations graphically by the use of *speed characteristics,* which were first published by the author in "The Electrician" of December 29th, 1883. Assume the case that the external electro-motive force is a fixed and constant quantity. What will be the relation between speed, power, and efficiency of, say, a series-wound motor? Since E_t is constant at all currents, we have practically an unlimited supply of electricity such as would be obtained from the mains in a system of town supply. The current passing through the motor will depend on its resistance, and on its counter-electro-motive force. The former is constant, whilst the latter increases with the speed. The faster we allow the motor to run the less current will flow through it, and the less power will be absorbed by it. Let in Fig. 57 the speeds be plotted as abscissæ, and the electrical horse-power absorbed as ordinates, then with a series-wound motor we obtain the curve $W\ W$. The exact shape of this curve depends, of course, on the construction of the motor, but its general character will be as shown. The easiest way of finding the curve experimentally is by attaching a brake to the motor, and loading it with different weights so as to produce different speeds. The horse-power absorbed by the brake can at the same time be plotted in the curve $w\ w$. If we begin with an excess of load on the brake, which will hold the motor fast, a maximum of current will flow, and a maximum of electrical energy will be absorbed without producing any external work. On the other hand, if we remove the brake altogether the motor will

attain a maximum velocity *o m*, and again no external work will be produced, but in this case very little current will pass, and the electrical energy absorbed will be a minimum. Between these extreme limits of no speed and maximum speed external work will be produced, and there is one particular speed, *o a*, at which this work will be a maximum. The ratio of the ordinates of *W* and *w* can be plotted in a curve, η η, drawn to any convenient scale, and this gives the commercial efficiency of the motor as a function of the speed. There is one particular

Fig. 57.



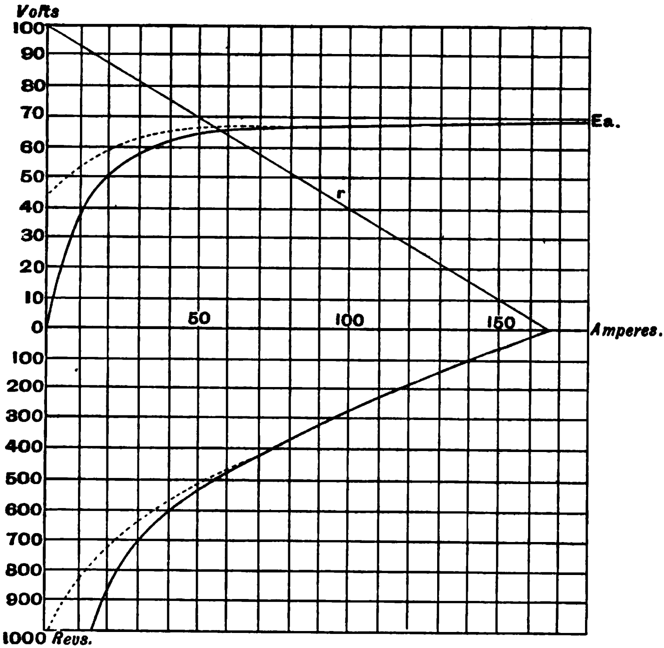
SPEED-CHARACTERISTICS OF SERIES MOTOR.

speed, *o b*, at which the efficiency is a maximum, but this is not necessarily the same speed as that for which the work is a maximum. As a rule it is considerably greater, and in actual work the motor should be so geared that it runs at or about the speed of maximum efficiency.

The experimental determination of the most economical speed, as just described, requires the employment of a dynamometer or brake, and if such an apparatus be not at hand, cannot be adopted. In this case a different method can be used, which is fairly reliable, although not quite so accurate as the actual power test. The question

to be solved is the relation between speed and current in a given series-wound motor supplied with current at a constant electro-motive force. This question can be solved if we know the internal resistance of the motor and its internal characteristic. Having obtained the rela-

Fig. 58.



RELATION BETWEEN SPEED AND CURRENT IN SERIES-WOUND MOTOR.

tion between speed and current, we can construct the diagram Fig. 57, making a certain allowance for the efficiency of conversion. Let, in Fig. 58, $O\ E_a$ represent that curve for a constant speed of say 500 revs., and let the inclined straight line, r, be drawn across the diagram at such an angle with the horizontal that its geometrical

tangent is numerically equal to the internal resistance of the motor in ohms, then the ordinates of the line, r, represent the counter-electro-motive forces created in the coils of the armature at variable currents. Thus, at 100 amperes, the counter-electro-motive force is 40 volts. If the armature revolves at a speed of 500 revolutions a minute, we see from the characteristic that its counter-electro-motive force is 68 volts, and to bring the latter down to 40 volts, so that a current of 100 amperes may pass, the speed will have to be reduced in the proportion of 68 to 40. The speed corresponding to a current of 100 amperes is therefore $500.\frac{40}{68} = 294$ revolutions. Similar calculations can be made for other values of current, and the speeds obtained can be plotted in a curve shown in Fig. 58, below the horizontal. At 166 amperes the speed is zero, because the whole of the constant electro-motive force available of 100 volts is required to overcome the internal resistance of the motor, leaving nothing to be opposed by counter-electro-motive force. At 16 amperes the speed is 1000 revolutions, and at smaller currents the speed might be still greater. Theoretically, it should be infinite if no current passes, and this would be the case if the motor were free to revolve without doing any work, and if there were no internal mechanical losses. This, of course, is an impossible condition, and a limit is set to the speed by the work which must be done to overcome mechanical and magnetic friction. In good motors this is, however, comparatively small, and consequently the speed of the motor, when running empty, is inconveniently high. This is a great drawback in many cases, especially where motors are required to drive lathes and other machinery offering a variable resistance. The example represented

in Fig. 58, applies also to the case where a series-wound motor is worked from a set of secondary cells, having a very low internal resistance, as the electro-motive force is then approximately constant at all currents. To lessen the difference in speed it is usual to insert a rheostat or variable resistance into the circuit between the cells and the motor. A maximum of resistance is inserted when the motor is running empty, and as the load increases resistance is switched out so as to regulate the speed. At best this is a clumsy device, requiring personal attention, and not very efficient, as with it variations in speed can never be altogether avoided. It is also wasteful, the heat developed in the artificial resistance being so much power lost. A better plan is to wind the field magnets of the motor on the compound principle, both main and shunt coils magnetizing in the same direction. This will raise the early part of the characteristic as shown in dotted lines, and will reduce the speed as shown also in a dotted line. This method is not a complete cure for the evil, but it is a palliation of it which in practice proves very successful. To make the motor perfectly self-regulating, it would be necessary to let the main coils on the field magnet excite the latter in an opposite sense to the shunt coils; but then a very valuable quality of the series motor, viz., its great starting power, would be lost. If a motor is employed for railway or tramway work it is very important that there should be an excess of power at starting. This condition is admirably fulfilled by the ordinary series-wound motor, since the current, the strength of the field, and the statical effort or torque are all maxima when the motor is at rest and decrease as it gathers speed. There is thus an automatic adjustment between speed, power, and resistance. Take, as an example, an electric

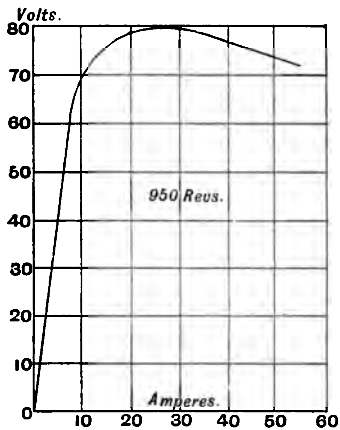
tramcar worked by accumulators. On a heavy gradient or bad part of the rod, the speed is low, allowing a large current to pass through the motor, thus providing the extra amount of tractive force necessary; on a good level road the speed will increase, less current will pass through the motor, and less tractive force will be developed. But on a downward incline, when no tractive force at all is necessary, the motor, and with it the car, would acquire too high a speed if not checked in some way. This was one of the difficulties encountered in the early forms of Mr. Reckenzaun's electric tramcar, worked by accumulators. Each car was provided with two series-wound Reckenzaun motors, gearing by means of a worm and wheel directly with the axles of the car. On a very good level road, and on downward gradients, it was necessary to continually handle the brake in order to prevent the motors running too fast. This defect has been removed in the later forms of electric tramcars; the motors are wound on the compound principle, and thus a certain initial strength of field is maintained whereby the speed of running light is reduced to a safe limit.

Hitherto we have assumed that the internal characteristic giving the electro-motive force as a function of the exciting power is the same for all currents flowing through the armature. This is not strictly accurate. Experiment shows that the greater the current flowing through the armature the smaller is the electro-motive force. The reduction is greater than that which corresponds to the product of resistance and current, and thus we are forced to the conclusion that, apart from the passive electrical resistance of the wire, there is some other element tending to lower the electro-motive force. The reason is not far to seek. When a dynamo is at work

each coil on the armature is alternately traversed by currents in one and the other direction, the change taking place each time the coil passes under one or the other brush. When a coil passes under one of the brushes it is for the time being short circuited in itself, and since a moment before it was traversed by half the total current, its self-induction will cause a gradually diminishing current to flow in it after it has been short circuited by the brush. By the time the coil emerges on the other side of the brush that current may not yet have died out, and will cause a spark, especially since at that moment half the total current is forced through it in an opposite direction. To avoid the spark we are forced to shift the brushes forward a certain distance beyond the neutral diameter, and it is well known to all who have to do with dynamos that the advance must be the greater the greater the current. The immediate result of shifting the brushes forward is to bring the coil in its short circuited state into a part of the field where there are lines already tending to produce an opposite current. In consequence of this the current circulating by self-induction will not only be extinguished the sooner, but the opposite current will be started, and if the brushes are properly placed it will have grown to half the strength of the total armature current by the time the coil emerges from under the brush. In that case there will be absolutely no spark, but those lines which were instrumental in toning down the violence of the change in the direction of the current are lost for the production of electro-motive force, and it is easy to see that this loss must be felt the more the greater the current. The next result of the shifting of the brushes is to bring the poles induced by the armature current, in the core of the latter, somewhat nearer to the field magnet

poles of the same sign, thus pushing the latter forward and distorting the field. This, at the same time, weakens the field, and thus the electro-motive force is again reduced. In good dynamos the total reduction of electro-motive force due to these two causes should not be more than about 5 per cent., but in badly designed machines, especially in those with weak field magnets, the reduction is often very great. Even in fairly good machines the

Fig. 59.



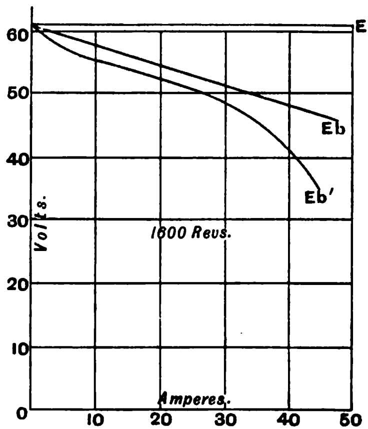
INTERNAL CHARACTERISTIC OF A GRAMME DYNAMO.

reduction may, with heavy currents, become considerable, and show itself in the internal characteristic, as will be seen from Fig. 59, which represents that of an A Gramme dynamo tested by M. Marcel Deprez.

This behaviour of the dynamo can best be studied with separately excited machines, and Mr. Esson has made very careful trials on the subject, which were published in April, 1884, in "The Electrical Review." The dynamo experimented upon was a "Phoenix" machine with

Pacinotti armature. It was separately excited and kept running at a constant speed of 1,600 revolutions a minute, whilst the current which was permitted to flow through the armature was varied by means of a rheostat. The line E, Fig. 60, represents the internal electro-motive force corresponding to the constant exciting power if there were no reactions. The line Eb represents the electro-motive force which would be found at the brushes if

Fig. 60.

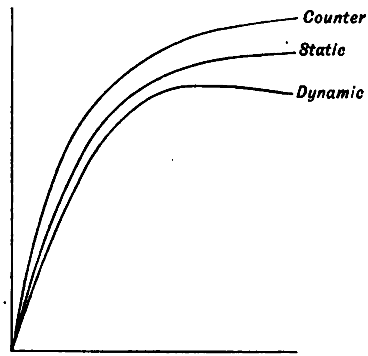


EXPERIMENT WITH PHŒNIX DYNAMO.

there were no reaction, and the line Eb^1 was that actually observed. The difference of the ordinates of Eb and Eb^1 represents the loss of electro-motive force due to self-induction, weakening and distorting of the field. The same influences which tend to lower the electro-motive force of a dynamo tend, on the other hand, to increase the counter-electro-motive force of a motor. This has been investigated by the author, experimentally, by separately exciting the field magnets of a Bürgin dynamo, and mea-

suring the electro-motive force under the following three conditions: 1st, No current was allowed to flow through the armature; 2nd, A current was allowed to flow doing external work by heating resistance coils; 3rd, A current from another dynamo was sent in an opposite direction through the armature, causing it to revolve and produce external work on a Prony brake. We have now to dis-

Fig. 61.



tinguish between the *static electro-motive force* found by experiment 1; the *dynamic electro-motive force* found by experiment 2; and the *counter-electro-motive force* found by experiment 3. By repeating the experiments under different conditions, three internal characteristics were obtained occupying relatively to each other the position shown in Fig. 61.

CHAPTER V.

Graphic Treatment of Problems—Maximum External Energy—Maximum Theoretical Efficiency—Determination of best Speed for Maximum Commercial Efficiency—Variation of Speed in Shunt Motors—The Compound Machine as Generator—System of Transmission at Constant Speed—Practical Difficulty.

THE treatment of problems relating to the electrical transmission of energy is greatly simplified by the use of the curves explained in the preceding chapter, and by other graphic methods, of which we may mention that due to Professor Silvanus Thompson. The problem is as follows. Let a square $A\,B\,C\,D$ be drawn so that the length of one of the sides shall represent the electromotive force E of the supply to any convenient scale, Fig. 62, and let the counter-electro-motive force e of the motor be represented by the length $A\,F = A\,G$. Draw through F and G the lines $F\,K$ and $G\,H$ respectively parallel to $A\,B$ and $A\,C$. The energy supplied to the motor equals the product of electro-motive force E and current C, whilst the work converted into mechanical energy in the armature of the motor equals the product of counter-electro-motive force e and current C. Let R represent the total resistance in the circuit, then $C = \frac{E - e}{R}$, which in our diagram is represented by the length $F\,C$ divided by R. The energy delivered to the motor is evidently

$$\frac{E\,(E - e)}{R},$$

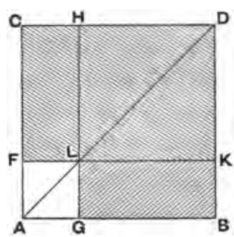
and that converted in the motor is

$$\frac{e\,(E - e)}{R}.$$

Now the area of the rectangle $F\,K\,D\,C = E\,(E - e)$ and the area of the rectangle $G\,B\,K\,L = e\,(E - e)$; and since R is a constant, we find that these areas—shaded in our diagram—are proportional to the work expended and recovered.

Thompson's diagram can immediately be used to solve

Fig. 62.



graphically two of the problems which have already been treated analytically in the first chapter (page 38). These are the following: First, what is the condition of maximum work obtained from the motor? and, secondly, what is the condition of maximum efficiency?

The answer to the first question is easily found by inspecting our diagram, Fig. 62. Since the rectangle $G\,B\,K\,L$, which represents the work of the motor, is inscribed between the diagonal $A\,D$ and the sides $A\,B$, $D\,B$; the question resolves into that of finding which of all possible rectangles inscribed within these lines has a maximum of area. This is evidently a square, the sides

of which are half as long as those of the external square. In this case the work expended is represented by a rectangle of half the area of the external square, and the efficiency is therefore 50 per cent.

We have: Work expended $\frac{1}{R}\frac{E^2}{2}$.

„ Work recovered $\frac{1}{R}\frac{E^2}{4}$.

„ Efficiency $\eta = 0{\cdot}50$.

As regards the second question it will readily be seen that the discrepancy in the area of the two rectangles, Fig. 62, is the greater, the nearer the point is to A, or in other words, the smaller the counter-electro-motive force. In the same measure as the latter increases, point L is pushed further towards D, and the areas of the two rectangles become more and more equal. The efficiency, therefore, tends towards unity as the counter-electro-motive force of the motor tends towards the electro-motive force of the source of supply of electricity. This statement has already been made in the first chapter, and it is theoretically quite accurate; but from a practical point of view it requires some qualification. It will be seen that when the counter-electro-motive force of the motor approaches very closely the electro-motive force of the supply, the current becomes very small, and the work expended and converted becomes also very small. Now the work converted in the motor is not all available in the shape of external mechanical energy, and it may well happen that in this case, after the resistance of mechanical and magnetic friction has been overcome, no margin remains for useful external work. The commercial efficiency would therefore be Zero, although the theoretical efficiency is a maximum. To put the matter

in another way: a certain minimum of current is required to overcome the friction of the motor, quite apart from any external resistance. It has been shown that with a constant field the torque of the motor depends only on the current which passes through the armature, but is independent of the speed. We may apply this law with sufficient approximation to the present case and assume that at all speeds the current which is required to overcome the internal friction of the motor is constant. Let γ represent this minimum of current, which will just keep the motor alone going, then $\frac{E - e}{R} - \gamma$ is the current doing useful external work, and the commercial efficiency is

$$\eta = \frac{e}{E} \cdot \frac{\frac{E - e}{R} - \gamma}{\frac{E - e}{R}}$$

$$\eta = \frac{Ee - e^2 - e R\gamma}{E^2 - Ee}.$$

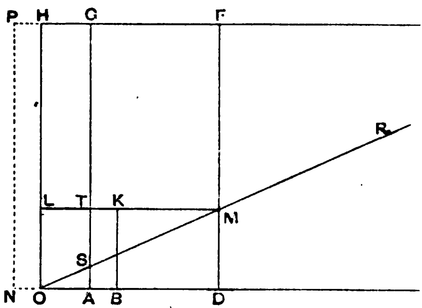
To find the condition under which η becomes a maximum we put $\frac{d\eta}{de} = O$ and obtain

$$(E - e)^2 = E R\gamma \quad \ldots\ldots\ldots \quad 29).$$

This formula is capable of graphic representation. Let in Fig. 63 $O A$ represent the current γ, which is required to keep the motor revolving at or near its normal speed when no external work is being done, and let $O H$ represent the electro-motive force E of the source, which we suppose to be constant for all conditions. This would be practically the case if the source of current were a self-regulating dynamo, or a set of secondary batteries having a very low internal resistance. The area of the rectangle $O A G H$ represents the number of watts required to overcome the

friction of the motor at its normal speed when doing no external work, and if the motor be shunt-wound, or compound-wound for constant speed, its strength of field will not greatly vary when external work is being done, and we may with a reasonable degree of approximation regard the area of the rectangle $O\ A\ G\ H$ to represent the internal loss of energy in the motor under all conditions. Draw $O\ R$ at such an angle to the horizontal that its geometrical tangent is numerically equal to the total electrical resistance of the motor and the line, then $S\ A$

Fig. 63.



represents the loss of electro-motive force corresponding to the current $O\ A$, $M\ D$ represents the loss corresponding to the current $O\ D$, and so on. Produce $O\ N = S\ A$ and complete the rectangle $O\ N\ P\ H$ (dotted in our diagram). The area of this rectangle is evidently equal $E\ R\gamma$, and if we produce a square $O\ B\ K\ L$ of equal area, the side $O\ L$ will be equal to the square root of $E\ R\gamma$, and will, according to equation 29) represent $E - e$. Hence it follows that if we so load the motor that its counter-electro-motive force $e = H\ L$, it will work with maximum commercial efficiency. The energy obtained at the motor spindle is represented by the area of the

rectangle *G F M T*, the energy expended at the source of electricity is represented by the area of the rectangle *O D F H*, and the ratio of the two is the commercial efficiency.

In the preceding chapter it was shown how, by the use of an absorption dynamometer, the speed for a maximum commercial efficiency can be found experimentally; it was also shown how, in the case of a series-wound motor, this determination can be made with a fair degree of approximation even without the use of a dynamometer. We can now employ the relations just found to make this determination for shunt or compound-wound motors also, without requiring the use of a brake. This can be explained by an example from actual practice. One of the author's dynamos (shunt-wound and designed to feed sixty incandescents) was used as a motor. The electro-motive force of the source, which was a compound-wound dynamo, was 100 volts, current through motor when running empty was 4 amperes, speed 1,100 revs., and resistance of line and motor ·2 ohm. We have now $R \gamma = \cdot 8$ and $\sqrt{E R \gamma} = \sqrt{80} = 8 \cdot 94$. To obtain best efficiency the motor must therefore be so speeded that its counter-electro-motive force $e = 100 - 8 \cdot 94$

$$e = 91 \text{ volts.}$$

When running empty the counter-electro-motive force is

$$100 - 0 \cdot 8 = 99 \cdot 2.$$

The best working speed is therefore

$$1100 . \frac{91}{99 \cdot 2} = 1010 \text{ revolutions.}$$

The current passing at that speed is 45 amperes, of which 4 amperes are required to overcome the internal friction of the motor, leaving 41 amperes to produce useful external work. By gearing the motor to the speed of

1010 revolutions a minute, we shall therefore obtain $\frac{41 \times 91}{736} = 5{\cdot}07$ H-P, actually available on the motor spindle.

But it is not always possible to keep the motor running exactly at the right speed, especially if the load should vary, and in this case it becomes important to know how far on either side of the best speed a variation may take place without seriously reducing the efficiency. For the motor above cited we find the following figures:—

1010 revs.	5·07 H-P.	$e = 91$	$c = 45$	82·8%	Com. effic.
1065 „	2·07 „	$= 96$	$= 20$	76·7	„
944 „	8·20 „	$= 85$	$= 75$	80·0	„

It will be seen from this table that a shunt-wound motor is fairly self-regulating, the range of speed between no load and full load being only about 15% in the present instance. It should be here remarked that the motor described is intended for a working current of 45 amperes, and should not be loaded to more than 5 H-P for continuous work. This reduces the extreme variation in speed to something under 9%. To show the influence of the resistance of the armature on the best speed and efficiency, a table is added, calculated for the same motor and the same electro-motive force, but with an additional resistance of ·3 ohm in the circuit of the armature, making $R = {\cdot}5$.

950 revs.	2·82 H-P.	$e = 86$	$c = 28$	73·5%	Com. effic.
860 „	4·30 „	$= 77$	$= 45$	70·5	„
1000 „	1·96 „	$= 90$	$= 20$	72·0	„

In practice, however, the additional resistance would not be placed in the circuit of the armature, but in the line, where, indeed, it is unavoidable if the transmission of energy has to be made over a considerable distance.

By inserting the resistance into the armature circuit only, we have not disturbed the condition under which alone formula 29) gives the best speed, viz., that the strength of the field shall be the same for all currents and speeds. This condition might be fulfilled even in the case of a transmission to a considerable distance if we excite the field of the motor separately or by a pair of separate wires from the distant source, but in practice such an arrangement would be too complicated and, as we shall see presently, it would have no advantage in point of constancy of speed over the simpler plan of exciting the field of our shunt-motor direct from the line which brings the working current. The effect of an increased resistance in the line is in the first instance to lower the electro-motive force at the terminals of the motor. With a constant strength of field this would naturally lower the speed of the motor, but if its field magnets are not excited to the saturation point, the reduction of electro-motive force at the terminals of the motor will result in a reduction of the strength of the field, thus allowing more current to pass through the armature by which its torque and speed is increased until its counter-electro-motive force again balances the reduced electro-motive force of the supply. The variation of speed will therefore be smaller than would at first sight appear. But a little consideration will show that the gain in speed due to the increased armature current can never quite compensate for the loss of speed due to the reduced electro-motive force, and thus a pure shunt-wound motor, if fed from a source of constant electro-motive force can never be perfectly self-regulating. It must run faster when the load is thrown off, and it must run slower if more work is put on it. We found the same to be the case with the pure series-

wound motor, but in a more marked degree. In this respect the shunt motor is preferable, as will be seen from the above tables (page 133), as its speed when running empty is only slightly higher than when loaded, whereas the speed of the series motor when running empty is excessive. On the other hand, the shunt motor has no starting power, since its armature, when at rest, forms a short circuit of very low resistance. To start a shunt motor it is necessary to arrange the switch in such manner that the field becomes excited before the current is allowed to flow through the armature, and to avoid excessive sparking or heating of the armature, in cases where the motor has to start with the load on, additional resistances must be placed into the armature circuit, which are again cut out as soon as the motor has attained some speed.

We shall now investigate the problem in what manner the electro-motive force of the source of supply must be varied in order to produce constant speed in a shunt-wound motor working under a varying load. Not to complicate the problem too much, we assume that the field magnets of the motor are, with the normal electro-motive force, excited to a very high degree, so that any slight variation in the magnetizing current cannot produce any material difference in the strength of the field. Under this condition the counter-electro-motive force in the armature of the motor will vary directly as the speed; and since the latter is to be constant, the former will also be constant for all loads. Let γ represent the armature current if the motor runs without load, let c be the current when there is a load, and let e be the constant counter-electro-motive force, then $(c-\gamma)\,e$ represents the external mechanical energy; and since e and γ are both

constants, a variation of external energy, or, as we call it, a variation in the load of the motor, makes it necessary to vary the current c through its armature. This is done by raising the electro-motive force E of the supply if the load increases, and lowering it if the load decreases. Let R be the resistance of line and armature, then $c = \frac{E - e}{R}$ and $E = e + c\,R$. We neglect as very small the amount of current required for the shunt on the field magnets. The equation shows that to maintain a constant speed of the motor the electro-motive force of the source ought to increase with the load. Its lowest value, when there is no load, will be $E = e + \gamma\,R$, and its highest value will be when load, and consequently current, are both maxima. The difference between the lowest and highest value will be the less, the smaller the resistance R of line and armature, but it can never entirely vanish, for that would require a line and an armature of no resistance. From the above considerations it will be seen that two shunt-wound dynamos can under no circumstances form a system of transmission of energy at constant speed of the receiving machine, because the electro-motive force of the generator —which we suppose to be driven by some prime mover at a constant speed—decreases as the current given out increases, whereas the motor requires exactly the opposite relation between these quantities. A shunt motor might be made to run at a constant speed by using an over-compounded dynamo for the generator. The principle of the compound-wound dynamo, or, as it is also called, of the self-regulating dynamo, is so well known that a few words only of explanation will suffice.

Let the field magnet of a dynamo machine be wound with two coils, one of fine high resistance wire coupled

direct to the brushes, and the other of stout low resistance wire, coupled in series with the brushes and the external circuit. If the latter be open no current passes through the main or series coils, and the magnetism of the machine is entirely due to the exciting power of the shunt coils. If the machine is properly designed, this amount of magnetism should produce an internal electro-motive force exactly equal to that which it is desired to maintain at all currents in the external circuit, provided the dynamo is driven at a constant speed. If a current is permitted to flow through the armature, the electro-motive force measured at the brushes is naturally somewhat less than that created within the armature coils, on account of losses through resistance and self-induction, the loss increasing with the current. To compensate for this loss it is necessary to increase the internal electro-motive force, and this is accomplished by an increase in the strength of the magnetic field. This is brought about automatically by the main current itself, which assists the shunt current in exciting the field magnets. In a correctly compounded machine the increase of magnetization due to the main coils is just sufficient, and no more than sufficient, to keep the external electro-motive force constant at all currents which can safely be passed through the machine. We say the machine is accurately compounded for constant electro-motive force.

Now it is easy to see that we can overdo the thing, by putting on somewhat finer shunt wire, which will lower the electro-motive force when the machine works on open circuit or on a circuit of high resistance; and by increasing the number of main coils so as to make the exciting power of the main current preponderate over that of the weaker shunt. In this case the increase of internal

electro-motive force will more than counterbalance the loss through self-induction and resistance, and the result will be that up to a certain limit the external electro-motive force will rise as the current increases. Such an over-compounded machine could therefore be used as a generator, the receiver being an ordinary shunt machine, and we would thus obtain a system of transmission of energy at constant speed.

Theoretically this is quite correct, but in practice there arises a difficulty due to the fact that the polarity of a compound machine can easily be reversed, especially if the influence of the main coils is considerably greater than that of the shunt coils. The author has attempted to establish such a system of transmission of energy at constant speed, but failed for the above reason. The failure was, however, more instructive than would have been the case had the system worked with theoretical perfection, and an account of it was published at the time in "The Electrician" (April, 1885), of which the following is an abstract:—

"A series-wound dynamo, when used as a motor, runs in the opposite direction to that in which it has to be driven when used as generator. To make the machine run in the same direction (call it forward), the coupling between field and armature must be reversed. With a shunt machine this is not so; the coupling between field and armature remains the same when used as a motor, and it runs always forward. The shunt machine used by the author was driven by a current from an over-compounded dynamo, the shunt of which was weak as compared to the main coils; and when the motor was doing little or no external work it behaved in a most erratic manner, running backward and forward alternately. At

every reversal excessive sparking took place at the brushes of both the motor and generator, and it was clear that both machines were overstrained and would speedily come to grief if the circuit were not interrupted. To explain what takes place under these circumstances we will start with the assumption that the generator is kept running at a constant speed, and that the motor is switched on whenever power is required. This is the usual practice where motive power is used at intervals for industrial purposes. Since the leads from the generator remain always charged, the moment we switch the motor on, a large current will pass through its armature and a small current through its magnets. As the motor is at rest there is no counter-electro-motive force to oppose the flow of electricity through the armature, and the result is a momentary excess of current. The immediate effect of this is to start the armature revolving at a high speed before the magnets have had time to become fully excited, for it must be remembered that an armature will revolve in a non-excited field, though with considerable waste of current. The speed required to produce a given counter-electro-motive force is the greater, the weaker the excitation of the field, and hence the motor starts off at a much faster speed than it would have in regular work with its magnets fully excited. On account of self-induction in the shunt field magnet coils, which is considerable, the magnets require some time to become fully excited, and whilst the strength of the field is growing the armature is gathering speed and storing mechanical energy. When at last the field magnets are saturated, the armature of the motor has attained such a speed that its counter-electro-motive force not only equals, but exceeds the difference of potential maintained between the leads by the

generating dynamo, and the current is forced back into it. For the time being the motor acts as a generator, the energy stored mechanically in its revolving armature being returned to the circuit in the form of current. This reverses the polarity of the compound dynamo (its shunt coils being weak, as stated above), and now both the generator and the armature of the motor are working in series, the generator assisting instead of opposing the current started by the motor. At this moment we have the following state of things:—The field magnets of the motor have just attained their maximum of magnetization with their original polarity; the polarity of the generator has been reversed, and an excessive current, in an opposite direction to that which produced motion, flows through the armature of the motor. Consequently the latter is quickly brought to rest, and started backward at a high speed. It now opposes a certain counter-electromotive force to the current from the generator, but it is not an increasing force as before. It is a decreasing one, because the original excitation of the motor field magnets is gradually vanishing, by reason of the reversal of polarity in the main leads, from which these shunt coils are fed. Just as it took a certain appreciable time of several seconds for the magnets to become excited, so does it take time for them to lose their magnetism. Eventually there arrives a moment when all the original polarity in these magnets has vanished, and when, therefore, the force impelling the armature to run backward has also ceased, though there is still an excessive current passing through it. A moment later the armature comes to rest, and begins to run forward again at a high rate of acceleration, when the whole cycle of phenomena just described is repeated, but this time with a current in the

reverse direction to the first. The third cycle will start with a current in the same direction as the first, the fourth cycle will start with an opposite current, and so on."

A similar phenomenon was observed by M. Gérard-Lescuyer, who used a Gramme series-wound dynamo as a generator, and a magneto machine as a receiver. He called the phenomenon an electro-dynamic paradox, and a description of it will be found in "The Engineer" of Sept. 17, 1880.

CHAPTER VI.

Classification of Systems according to Source of Electricity—Transmission at Constant Pressure—Motors mechanically governed—Self-Regulating Motors—Transmission at Constant Current—Difficulty of Self-Regulation—Motor for Constant Current made Self-Regulating—Application to Transmission over large Areas—Continuous Current Transformator—Transmission between two Distant Points—Loss of Current by Leakage—Theory—Commercial Efficiency—Conditions for Maximum Commercial Efficiency—Self-Regulation for Constant Speed—Practical Example.

It will be necessary to distinguish between different systems of electric transmission of energy, according to the source of electricity. An almost endless variety of cases may present themselves in different applications of electrical transmission, but three systems are of special interest, because most frequently occurring in practice. These are the following:—

1. Transmission of energy from primary or secondary batteries at short distances to one motor only.

2. Transmission of energy from one or several dynamos to a number of motors placed upon the same circuit, but working independently of each other.

3. Transmission of energy between two distant points by means of one generator and one motor.

We may also make another classification according as the motors are intended for a constant or variable load, or a constant or variable speed. Generally speaking, the systems of transmission coming under heading 1) are not required for a constant load, nor is it of any great impor-

tance that the speed should remain constant under a variable load. We shall not enter into a minute description of these cases here, as the investigation of electric tramways and railways, worked by accumulators, will afford ample opportunity of entering into details.

System 2) is that presenting most difficulties on account of the condition that all the motors must be independent of each other. The case is further complicated by the requirement that each motor should run with the same speed when empty or loaded. A moment's consideration will show that the last condition is an absolute necessity if we would make the electric transmission of energy of real practical use to small domestic industries. The artisan or small manufacturer would have his motor connected to a common system of service leads, and whenever he required power he would switch the current on to his motor. In doing so he must not disturb any other work which, at the same time, may be done elsewhere from the same service mains, such, for instance, as lighting or working other motors; and further, his motor should always run at the same safe speed, whether it is giving him little or much mechanical energy. Most operations requiring the use of tools as turning, planing, &c., can only be properly performed at a certain fixed rate of speed, and the machinery must be kept going at that rate at all times.

System 3) presents difficulties of a different nature. Since we have to deal only with one generator and one motor, it is easier to make each fit the other, and as a rule the load is fairly constant, so that regularity of speed is not difficult to obtain. In this case the difficulty lies more in the necessity of proper insulation of line and machinery. Generally speaking, the system is required

for long distance transmission, and to obtain an economical arrangement, both as regards first cost and commercial efficiency, the use of a high electro-motive force is necessary. This entails some danger to human life, and some difficulty in maintaining an efficient insulation. Both these points can, however, be satisfactorily dealt with, if proper care is used in the design and execution of the work. As regards the danger to human life involved in the use of electric currents of high pressure, this is generally greatly overrated. It is quite possible for a man who with both hands should touch the positive and negative wires in a non-insulated part, to be killed or severely injured if the pressure is over two or three thousand volts, but the accident can be rendered almost impossible if due precaution is taken. A circular saw if only lightly touched whilst revolving will cut a man's finger off, and what can be more dangerous than a pair of powerful spur wheels? Yet we have found means of protecting life very effectually from destruction by purely mechanical means, and shall, without much difficulty, find means for protecting it from the electrical danger.

System 2) is best described as an electrical transmission and distribution of energy from one central station to several distant points. Now this distribution can be made on the parallel or on the series system. In the first case the electro-motive force (or pressure) between the positive and negative mains must be kept constant, and the motors are connected all in parallel from the mains; in the second case the current passing through the mains must be kept constant, and each motor, when at work, is traversed by the same current. The pressure at the station must be the greater the greater the number of motors at work. In the first case the pressure is kept

constant, but the current delivered into the mains must be the greater the greater the number of motors at work. We have thus to distinguish between *distribution at constant pressure* and *distribution at constant current*. The first system is represented—though as yet on a more restricted scale than was anticipated by the promoters—by the Edison system in New York and Berlin, the latter by the Thomson-Houston system.

Electric Distribution of Energy at Constant Pressure.

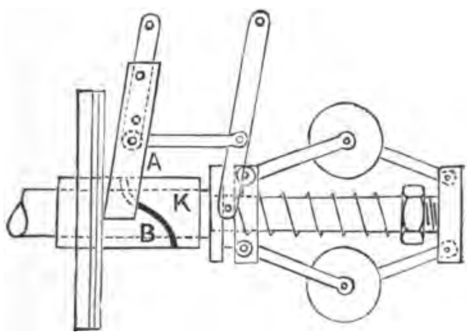
We must now inquire into the theoretical conditions of this case. It will be evident at the outset that for economical reasons any attempt to obtain constancy of speed by the use of artificial resistances can only lead to a partial and not very satisfactory solution of the problem, and had better not be made if other means are at hand. This, happily, is the case in the present instance. We have two means by which we can without waste regulate the power of the motor to the work and yet keep it running at a constant speed. First, we may apply a mechanical device by which the power of the electric current is cut off in proportion as the work is cut off, and, secondly, we may apply an electrical device in the shape of special winding of the field magnets of the motor by which the torque exerted by the armature is automatically regulated so as to correspond to the mechanical load. As regards the first system, which applies equally well to the distribution at constant pressure, and to that at constant current, Professors Ayrton and Perry have in a paper on Electro-Motors and their Government[1] shown how this can be done. They say: "The method of cutting off the

[1] "Journal of the Society of Telegraph Engineers and Electricians," No. 49, vol. xii. 1883.

power as hitherto employed has this serious defect, that instead of the power cut off being directly in proportion to the work cut off, the arrangements have been such that either all power was cut off or none, so that the motion of the motor was spasmodic, just as in an ordinary gas-engine, which suffers from the same defects, that full charge of gas or no charge are the usual only alternatives. An electro-motor governor of this type, which may be called a 'spasmodic governor,' consists merely of a rotating mercury cup into which dips a wire, which makes in this case contact with the mercury, and so completes the circuit when the speed is slow, but which, on account of the hyperbolic form assumed by the surface of the mercury as the speed rises, ceases to dip into the mercury at high speeds, and so breaks contact." Later on the inventors say: "The first improvement we made in governing consisted in replacing the 'spasmodic governor' by a 'periodic governor.' With our periodic governor the power is never cut off entirely for any length of time, but in every revolution power is supplied during a portion of the revolution, the proportion of the time in every revolution during which much power is supplied to the time during which less is supplied depending on the amount of work the motor is doing. Our periodic governor, then, differs from the spasmodic governor in the same way that a good loaded steam-engine governor differs from the ordinary governor of a gas-engine. One of the ways of effecting this result is as follows: a brush, *A*, Fig. 64, lies on the rotating piece, *B K*, the cylindric surface of which is formed of two conducting portions connected with one another through any resistance, and the brush, *A*, is moved along the cylinder *B K* under the action of the governor balls. When the brush *A* is touching the contact part *B*, the

motor is receiving current directly, but when it rests on the part *K*, the motor receives current through the resistance which is interposed between *B* and *K*. If the governor balls fly out, the brush is moved along *B*, *K*, so that there is contact with *K* during a greater part of the revolution than before; and if the governor balls come together, the speed of the motor being too small, the brush is moved in the opposite direction so that it makes

Fig. 64.



PERIODIC GOVERNOR.

contact with *B* for a longer time during each revolution. If the motors are in series, we arrange that the periodic governor shunts the current periodically, instead of introducing resistance. In this case the connections are as follows: *B* is made of wood, while *K* is made of metal. *K* is connected to one end of a shunt coil, the other end of the shunt being connected to one of the terminals of the motor and *A* is connected to the other terminal of the motor. If, then, *A* rests on *B*, the shunt is inoperative and all the current passes through the motor; whereas, if it rests on *K*, the shunt is in operation, and part of the current only passes through the motor." It

will be seen that both these governors invented by Professors Ayrton and Perry, have partially, at least, the fault of depending on artificial resistances whether they be used for parallel or series work. The loss of energy thus occasioned can be reduced by making the resistance high for parallel, and low for series work, and on purely theoretical grounds it could even be entirely prevented by making the resistance infinite, that is, breaking the circuit altogether during a portion of each revolution when working in parallel. But this would produce an unequal turning force, and would also entail destructive sparking between the brush, *A*, and the contact pieces *B* and *K*. Even if the resistance between *B* and *K* or that of the shunt coil between *K* and one terminal of the motor is fairly low, there seems to be some sparking ; for the inventors say in their paper that with any such governors it is difficult to entirely prevent sparking, and that on this account motors wound so as to be self-regulating without any mechanical device are preferable.

Broadly speaking, the self-regulating motor is the converse of the self-regulating dynamo wound for constant pressure. In a properly compounded dynamo the electromotive force or pressure at the terminals must remain constant, although the resistance of the external circuit may vary between wide limits, causing an inversely proportional variation in the external current. The power required is approximately proportional to the current. The machine works, therefore, under these conditions: Speed constant—Electro-motive force constant—Current variable—Power required to drive the machine also variable, but proportional to current. Now, in a self-regulating motor the conditions are:—Electro-motive force constant—Speed constant—Power variable—Current re-

quired to drive the motor also variable, but proportional to power.

It has already been pointed out that in a general way dynamo and electro-motor are convertible terms; and although there are cases when it is impracticable to work a motor as a dynamo, it is always perfectly easy to work a dynamo as a motor. From this general convertibility it is reasonable to expect that a properly compounded dynamo can without any alteration in the connection between its field magnet coils and armature, be used as a self-regulating motor, the only condition being that it shall be supplied with current at a constant electro-motive force. When speaking of a self-regulating motor in the sense that its speed of rotation shall automatically be kept constant whatever variation might occur in the load or mechanical resistance which the armature of the motor has to overcome, it must be understood that this refers only to such cases where the load varies between zero and a maximum not beyond the capability of the motor. If we throw an excess of load on to the motor, it will pull up or slacken speed, and thus cease to be self-regulating, just as the electro-motive force at the terminals of the best compound-wound dynamo will be lowered if we allow an excess of current to flow. But within a reasonable limit of load in the case of the motor, and a reasonable limit of current in the case of the dynamo, both machines can be made self-regulating, and this result is obtained by the same means, that is to say, the same winding which will make the dynamo give a constant electro-motive force, will make the motor run at a constant speed. This result might be expected on the ground of the general convertibility of these machines, but since it is of great practical importance, special proof

is desirable. This can be easily obtained from our formulas in Chapter III. According to equation 7) the torque exerted by an armature current, C_a, in a field of Z lines, is in absolute measure:

$$T = \frac{Z\,Nt\,C_a}{\pi}.$$

It is independent of the speed, and since Nt is constant for any given motor, the torque or turning moment exerted by the armature is directly proportional to the product of the strength of field and armature current. By increasing either or both these factors we are able to overcome our increased load. Since the electro-motive force is supposed to be constant, it is evident that a variation in load must be compensated mainly by a variation in current. Assuming that the ends of the shunt coils are coupled to the terminals of the motor—not to the brushes—we have, retaining the notation of Chapter III., the following equations:

$$Cs = \frac{E_t}{r_s} \qquad C_a = C_m.$$

$$E_b = E_t - r_m\,C_m \qquad E_a = E_t - (r_m + r_a)\,C_a.$$

The counter-electro-motive force E_a is, according to equation 5), expressed in volts by

$$E_a = Z\,Nt\,n\,10^{-8} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 5)$$

$$E_t - (r_m + r_a)\,C_a = Z\,Nt\,n\,10^{-8}.$$

Now the condition under which the motor is to be used is that the electro-motive force at its terminals E_t, shall be kept constant. We have, therefore,

$$\text{Constant } E_t = (r_m + r_a)\,C_a + Z\,Nt\,n\,10^{-8}.$$

Since the speed n must also remain constant if the motor is to be self-regulating at all loads, the only variables are C_a and Z, which have to satisfy the above equation. In

other words, we may regard the field Z as a function of the armature current C_a, and the condition that the motor be self-regulating is brought down to this, that the strength of its field shall depend on, and vary in a certain manner with the current passing through the motor.

$$Z = \frac{E_t - (r_m + r_a)\, C_a}{Nt\, n} \times 10^{-6}$$

We see by this equation that Z will be the smaller the greater C_a, and since C_a is almost directly proportional to the mechanical load of the motor, we arrive at this, at first sight, startling result: that the heavier the work we impose upon the motor, the weaker must be its field. It might have been thought that as additional load is thrown on, we ought so to arrange matters that the magnetism of the field magnets becomes strengthened, and able to exert an increased magnetic pull on the armature. But a moment's reflection will show that the effect of such an arrangement would be to reduce the speed. The magnetic pull exerted by the field magnets upon the armature does not depend on the strength of magnetism in the field magnets only, but is the product of that quantity and the current in the armature coils. An increase of pull may therefore be brought about either by making the field stronger, or by increasing the current in the armature, or by both means combined. If we make the field stronger, we not only increase the magnetic pull exerted on the armature, but we also increase the counter-electro-motive force, as will be seen from equation 5), page 81, and thus check, or at least reduce, the flow of current through the armature at the very moment when we want most power. The motor would thus run slower until its reduced counter-electro-motive force again allows a current to pass

of sufficient strength for the work imposed on the moto[r]. If, on the other hand, we seek the increase of power b[y] allowing more current to pass through the armature, w[e] do not increase the counter-electro-motive force, but w[e] have a slight increase in the loss of electro-motive forc[e] due to the resistance of the armature. To compensat[e] for this slight increase of loss, it is necessary to weake[n] the field somewhat for heavy currents, and thus bring about the reduction of counter-electro-motive force by a[n] amount corresponding to the increased loss of electro-motive force due to the resistance of the armature. If the motor runs without doing external work, C_a is almost zero, and we have the strongest field,

$$Z = \frac{Et\,10^6}{Nt\ n},$$

which is entirely due to the shunt coils. Let now a load be thrown on. The immediate effect will be to slightly reduce the speed. The counter-electro-motive force which previously was nearly equal to E_t, will thereby become somewhat reduced, thus allowing a considerable current to pass through the armature and the series coils of the magnets. This again accelerates the armature until the normal speed is reached. The direction of winding of the series coils must be evidently such that the main working current tends to *demagnetize* the field magnets. Now in an ordinary compound-wound dynamo, the series coils are wound and connected in such a way that the main current tends to *increase* the magnetism produced by the shunt coils. If we use such a dynamo as a motor, the current in the shunt coils will remain the same as before, the current in the armature will flow in the reverse direction, and therefore produce motion—instead of

resisting it, as is the case when the machine is worked as a dynamo ; and the current through the series coils will also flow in the reverse direction, thus tending to weaken the field magnets. It will be seen that these are precisely the conditions which our theory indicates as necessary, in order to make the motor self-regulating, and we find that it is correct to say that a compound-wound machine can be used either as a self-regulating dynamo or as a self-regulating motor. There may be slight differences in the exact proportion between shunt and series coils in both cases, but the general principle of compounding is the same for either purpose.

A question of considerable practical importance is that of the relation between the weight of the motor and the maximum of mechanical energy it can give out. Since that maximum must be given out when the field is weakest, whereas in a non-self-regulating motor the arrangements can always be so made that the maximum is given out when the field is strongest, it is evident that, for a given power, the self-regulating motor must be heavier. This is certainly a drawback, and it becomes necessary to know what price, in the shape of increased weight, we have to pay for the advantage of automatic regulation. Our formula for Z enables us to form a rough estimate of this increase in weight. The difference between the initial value of Z and the minimum value is due to the product $(r_m + r_a) C_a$. The greater this product, the more must the field be weakened, and the smaller is the maximum of power obtainable with a given weight of motor. It is therefore of importance to keep the product $(r_m + r_a) C_a$ as small as possible, and since C_a, which we must consider as the primary source of power, cannot be reduced, it is evident that the re-

sistance of series coils and armature should be as small as possible. Now, in a good modern motor, the loss of electro-motive force occasioned by the resistance of these parts, varies between 5 and 10 per cent. of the electromotive force applied at the terminals; take 7 per cent. as a fair average, and we find that if the initial field is represented by, say, 1,000 lines, the field at full work will contain 930 lines. Now if the motor were not self-regulating, the field at full power would contain 1,000 lines, and thus be able to develop about 7½ per cent. more mechanical energy. If, on the other hand, we wish the two motors to develop the same maximum of mechanical energy, the field magnets of the self-regulating motor would require to have 7½ per cent. more cross sectional area. Since series and shunt coils act differentially, a larger amount of copper is also required. This excess would probably amount to about 2½ per cent. of the total weight, so that in all the self-regulating motor will weigh 10 per cent. more than an ordinary motor which is not self-regulating. This does not seem too high a price to pay for the safety and general comfort of a self-regulating motor, and if once a service of electric light mains on the parallel system were laid down throughout certain populous districts in our towns, it would be perfectly practical to utilize the same mains for distributing motive power to artizans and small manufacturers by supplying them with such self-regulating motors.

Electric Distribution of Energy at Constant Current.

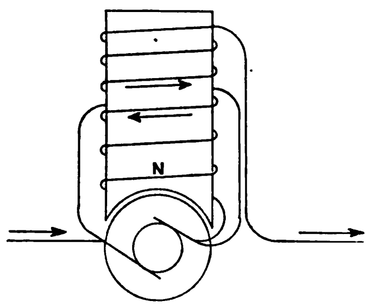
This problem is not of so easy solution as the distribution of energy at constant pressure, and the difficulty is a fundamental one. It lies in this, that there is no direct

connection between the speed of a motor and the current which flows through its armature. There is a direct connection between speed and electro-motive force, and, therefore, self-regulation is possible without the use of any external appliance in the shape of a mechanical governor or other apparatus which controls the power. But where the current is constant, some kind of external governor is necessary. This follows also immediately from M. Marcel-Deprez's experiments cited in Chapter III., page 90. We have seen that the speed was totally independent of the current, the latter remaining throughout the range of each experiment practically constant, whereas the speed was in some cases increased five-fold, by simply increasing the electro-motive force of the source. When a number of motors are coupled in series, as would be the case in a general system of distribution, the difficulties are much increased. To test this matter experimentally the author has placed three precisely similar motors (series-wound) in series into the same circuit. The current was supplied by a dynamo, and the three motors were loaded by brakes to as near as may be the same amount. It was then found quite impossible to keep all three motors going for any length of time at the same speed. The least irregularity in the current, or the least variation in the friction of the brakes, would cause first one and then the other motor to come to rest, whilst the speed of the remaining motor increased to a dangerous extent.

Professors Ayrton and Perry have in the paper above mentioned proposed to make motors self-regulating if worked by a constant current in the following way: The field magnets, Fig. 65, are wound differentially with a fine wire coil, which is a shunt to the armature only,

and a thick wire coil which is in series with the armature and main current. The armature and shunt coil constitute a shunt motor, the armature and main coil a brake generator which is intended to absorb any surplus power if the load is thrown off. As far as the author is aware the system has not been tried in actual practice, and there are theoretical reasons for expecting that it would not work. From equation 7) it will be evident that the field must be strongest when the load is greatest. Now suppose that the differential winding could be so propor-

Fig. 65.

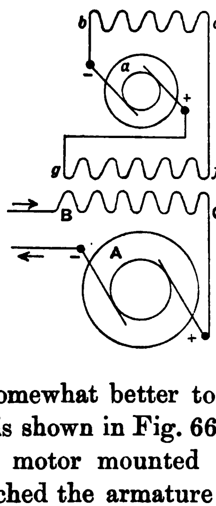


tioned that for a given load the field is exactly of the right strength to produce the normal speed. Now let a very slight additional load be thrown on. The immediate effect will be to slightly reduce the speed, and in consequence of the reduction in speed the magnetizing current in the fine wire coil will also be reduced. The field will thus be slightly weakened. This will further reduce the speed and again weaken the field, and so on, until the armature comes to rest. At that moment the magnetizing influence of the main coils, which is in the opposite direction to that of the shunt coils, will alone exist, and the

field magnet instead of presenting a *N* pole to the armature, as shown in the illustration, will present a *S* pole to it. The tendency must therefore be to reverse the motion, and thus the slight addition of load has not only brought the armature to rest, but actually caused a tendency to run backwards. Whether it will run backwards depends on the relative magnetizing power of the main and shunt coils.

An arrangement devised by the author, and which

Fig. 66.



seems to promise somewhat better to fulfil the condition of constant speed, is shown in Fig. 66. *A* is the armature of a series-wound motor mounted upon a spindle, to which is also attached the armature *a*, of a small series-wound dynamo which has no other work to do but to supply current for demagnetizing the field magnets of the motor. The main current magnetizes them in the direction, say, from *B* to *C*, the auxiliary current from the dynamo acts in the direction *f* to *g*, and tends to demagnetize them. *b c* is the field magnet coil of the dynamo. Now for each dynamo working on a closed

circuit of constant resistance, as in the present case, there exists a critical speed at which it will begin to give a current of some strength. Below that speed it gives hardly any current, and above that speed it gives almost at once the full current. The motor should be so geared as to run at the critical speed of the little auxiliary dynamo. If now an additional load be thrown on, the immediate result will be to reduce the speed of the motor, thereby causing the armature of the dynamo to run below its critical speed. The dynamo will thus partly or entirely lose its current and the demagnetizing influence which previously has kept the field below its full strength, will to a greater or lesser degree be withdrawn. The strength of the field will thus be increased, and an additional magnetic pull will be brought to act on the armature, by which it can overcome the increased load. In case the load be entirely thrown off, the motor will have a tendency to race, but this tendency will be immediately checked by the auxiliary dynamo, the current from which increases considerably with a very slight increase of speed. Its demagnetizing influence is thus enormously increased, and the field of the motor is weakened to such an extent that there is just power enough left to drive the dynamo but no more. To make this arrangement successful it is necessary that the field magnets of the auxiliary dynamo be made of very soft iron, so as not to retain any considerable amount of permanent magnetism, which would alter the critical point as between an increasing and decreasing speed. The more sensitive and unstable the dynamo can be made, the better. For this reason it is also necessary to place the two armatures a considerable distance apart on the same spindle, so that the field magnets of the motor may

not induce magnetism in the field magnets of the dynamo, and thus disturb the critical point. In practice it would probably be found necessary to place a bearing between the two armatures, and that could easily be so shaped as to act as a screen between motor and dynamo.

The importance of having self-regulating motors of this description cannot be over-estimated. If we would distribute electrical energy over a considerable area it is absolutely necessary to work at high pressure, otherwise the cost of copper in our mains becomes prohibitive. On the other hand, we cannot, under the provisions of the Electric Lighting Act, 1882, employ in our houses a higher electro-motive force than 200 volts, and even that is seldom employed, since for incandescent lighting in parallel connection we are limited by the electro-motive force of the lamps, which as yet has not much exceeded 100 volts. Lamps of greater voltage can be made, but are as a rule too delicate for ordinary use. In a system of general supply we would thus be practically compelled to distribute electricity at the exceedingly low potential of 100 volts. As Professor G. Forbes, in his Cantor Lecture at the Society of Arts, has pointed out, the transmission of electric energy at so low a potential would require the use under our streets of copper conductors half an inch thick and many yards wide. This is quite out of the question, and some means of economizing copper must be discovered before we can attempt to transmit electric energy to any distance. Professor Forbes, in the course of lectures above mentioned, has shown several methods by which a reduction in the cost of mains can be attained. Of this question more is said in Chapter VII. For the present it will suffice to point out that the system of transmitting energy by so-called secondary generators is the

most likely to effect the desired object, but, being based on alternating currents, is not suitable for general purposes of motive power. By the use of self-regulating motors, such as the one described above, we can, however, not only transmit the electrical energy of a high tension current over a long line of consuming centres, but we can also transform it into the energy of low tension currents at these centres, which currents would have to be distributed over a limited area only, and thus not require any excessive amount of copper for mains. Such a transformator, for continuous currents would consist of a self-regulating motor with auxiliary dynamo and a self-regulating dynamo wound for constant electro-motive force. The three armatures could be mounted on the same spindle, and the whole apparatus could be self-contained. The co-efficient of efficiency of a transformator of this type would be slightly lower than that of an alternating current transformator, because on account of having a revolving part, certain mechanical losses would be incurred. But the efficiency would still be fairly satisfactory; probably about 75 per cent. of the energy of the high tension current could be recovered in energy of the low tension current, and the saving of coal effected by producing the power originally by large engines at the central station would of course be very considerable.

According to the classification made in the beginning of this chapter we have now to consider

System 3), which comprises the transmission of energy between two distant points by means of one generator and one motor.

Let E_a, E_b, and E_t represent respectively the electromotive force in the armature, at the brushes and at the terminals of the generator, and let e_a, e_b, and e_t repre-

sent the same for the motor. Let R_a, R_m, represent the resistance of the armature, and magnetizing coils of the generator, and r_a, r_m represent the same for the motor, then we have, according to the equations 15) to 22), if both machines are series-wound, the following relations:

GENERATOR.	MOTOR.
$E_a = E_b + CR_a.$	$e_a = e_b - cr_a.$
$E_b = E_t + CR_m.$	$e_b = e_t - cr_m.$
$E_t = E_a - C(R_a + R_m).$	$e_t = e_a + c\,(r_a + r_m).$

C being the current sent by the generator into the line, and c being the current received by the motor. If the insulation of the line were perfect, these two currents would be equal; but in practice some small leak of current from the positive to the negative circuit, when the line extends over several miles, can hardly be avoided, and therefore we must assume

$$C > c.$$

The loss of current $C - c$ represents, as far as the generator is concerned, a waste of energy expressed by the product

$$E_t\,(C - c) \text{ watts.}$$

As far as the motor is concerned, this leak not only reduces the current which is available at the receiving station, but it has also the effect of reducing the available electro-motive force e_t beyond the value corresponding to the current c. It will be clear that unless the leak occurs close to the generator, part of the line will have to carry a current larger than c, and thus the loss of electro-motive force due to the resistance of the line must be greater than the product of that resistance and the motor-current c. If the line is throughout its entire length equally well insulated, each unit of its length will have the same insulation resistance, which should be very high in com-

parison to the conducting resistance itself. In a perfect line it should be infinite, but, as remarked above, this is not obtainable in an overhead circuit going many miles across country. Let ς represent the conducting resistance of the line, and let i denote the insulation resistance between the positive and negative lead for unit length, then, if the distance from the generator to the motor be l, the total insulation resistance as measured on a Wheatstone bridge would be $\frac{i}{l}$. Knowing this from actual measurement, it might be thought that by the application of Ohm's law we could easily find the leak, $C - c$, by simply dividing the electro-motive force between the wires by the insulation resistance. This would, however, not be correct, for the simple reason, that the electro-motive force between the wires is not a constant, but diminishes in a certain ratio as we approach the distant end of the line, the actual law by which this diminution takes place depending not only on the resistance of the line and the current, but also on the insulation resistance itself. The question is therefore not so simple as it at first sight appears. An approximate solution sufficiently accurate for practical purposes is the following:

Let ε represent the electro-motive force between the leads at the distance x from the generator; let the distance be increased to $x + dx$ and the leak of current corresponding to length dx be dc, the drop in electro-motive force corresponding to that length being $d\varepsilon$. Then the following equations evidently obtain:

$$-d\,\varepsilon = c\,\frac{\varsigma}{l}\,dx.$$

$$-dc = \frac{\varepsilon}{i}\,dx.$$

From these equations we obtain

$$\varepsilon\, d\, \varepsilon = \frac{\varsigma}{l}\, i\, c\, dc,$$

and by integration

$$\varepsilon^2 - \frac{\varsigma\, i}{l}\, c^2 = \textit{Constant}.$$

To find the constant we apply the formula to the home end of the line, where $\varepsilon = E_t$, $c = C$, and obtain between that and the far end the relation

$$E_t^2 - e_t^2 = \frac{\varsigma}{l}\, i\, (C^2 - c^2),$$

from which we find

$$c = \sqrt{C^2 - \frac{l}{\varsigma\, i}\, (E_t^2 - e_t^2)}.$$

This gives the current arriving at the motor, but in a somewhat inconvenient form. To simplify the expression we develop the square root into a series, and since the second term is very small in comparison to the first we can neglect the second and subsequent powers.

$$c = C - \frac{1}{2}\, \frac{l}{\varsigma\, i}\, \frac{E_t^2 - e_t^2}{C}.$$

Now $E_t^2 - e_t^2 = (E_t + e_t)\, (E_t - e_t)$ and $\frac{i}{l} = J$, the total insulation resistance of the line. Hence

$$c = C - \left(\frac{E_t + e_t}{2}\right) \frac{1}{J}.\; \frac{E_t - e_t}{\varsigma\, C}.$$

The leak of current is

$$C - c = \left(\frac{E_t + e_t}{2}\right) \frac{1}{J}.\; \frac{E_t - e_t}{\varsigma\, C} \quad \ldots\ldots \quad 30).$$

Now $\frac{E_t + e_t}{2}$ is the average electro-motive force between the out and home lead; and $\left(\frac{E_t + e_t}{2}\right)\frac{1}{J}$ represents the current which under that average electro-motive force would flow through J, the total insulation resistance. This current, multiplied by $\frac{E_t - e_t}{\varsigma\, C}$, gives the actual leak. It will be observed that $\varsigma\, C$, being the product of a resistance and a current, represents a difference of potential, and in this case it represents the electro-motive force which would in a line of perfect insulation be required to drive the full initial current C through the circuit, supposing the far ends were in metallic contact. $\varsigma\, C$ represents, therefore, the loss of electro-motive force if there were no leak. The actual loss, $E_t - e_t$, is naturally somewhat greater, and thus the quotient between the two must always be greater than unity. From this it follows that the loss of current due to leakage along the line is slightly greater than the figure we obtain by dividing the average electro-motive force by the total insulation resistance. Where the insulation resistance is very high, and the conducting resistance very low, the leak will with sufficient accuracy be expressed by

$$C - c = \left(\frac{E_t + e_t}{2}\right)\frac{1}{J},$$

but when the conditions are less favourable formula 30) should be used.

It is necessary in this place to briefly consider the influence of the leak on the total efficiency of a system of electric transmission, especially with reference to the most economical speed of the motor. In text books, and in

scientific articles on the subject, the assumption is generally made that the insulation of the line is perfect. This may be so in some exceptional cases, but a general theory must include all cases ; it should, therefore, take the leak into account. As far as the writer knows, this has only been done by Professor Oliver Lodge in his treatise on the transmission of power by dynamo-machines, published in "The Engineer," 1883. It is also generally stated that the efficiency is the greater, the nearer the counter-electro-motive force of the motor approaches the electro-motive force of the generator. It has already been pointed out that this is quite wrong (see Chapter V., page 129), even if the motor be worked by a current of constant electro-motive force, such as would be the case if the generator were a self-regulating dynamo placed close to the motor, and connected with it by leads of practically no resistance and perfect insulation. But when the leads have considerable resistance, and especially if their insulation is not absolutely perfect, the statement above referred to and which is carefully perpetrated by successive writers, becomes still more erroneous. From equation 30) it will be seen that the leak is the greater, the greater e_r. At the same time an increase of e_r has the effect of checking, or at least diminishing, the working current c, thus reducing the amount of energy received. Since the energy lost by leakage increases with the counter-electro-motive force, whilst the energy actually given out by the motor at first increases with the counter-electro-motive force up to a certain point, but beyond it decreases again, it will be clear that high efficiency cannot be obtained by allowing the counter electro-motive force to approach too near to the electro-motive force of the generator. In the following investigation we shall

assume for the sake of simplicity that there is absolutely no leak in the line. The results obtained will, therefore, be to some extent inaccurate, but they can be rectified by using equation 30). Thus with a perfect line we would obtain certain values for $C = c$ and E_t; and the generator would have to give the current and electro-motive force thus determined. Now assume that, after a certain time, the line begins to leak. This will reduce the energy received by the motor, and consequently also that given out by it. It is evident that this loss can be compensated by running the generator at a higher speed; in other words, by increasing E_t and C beyond their original values. A similar plan we follow in the mathematical investigation. We assume at first that the insulation of the line is perfect, and we are thus enabled to use formulas of great simplicity. This gives a certain set of conditions for the generator. If the line is in reality in as perfect a state as assumed, the problem is solved. If, however, the line leaks, we rectify the values for E_t and C by using equation 30). This gives a new set of conditions for the generator, and the mechanical energy necessary for actuating the generator must be calculated for these new conditions. The conditions of the motor are not altered thereby.

The electro-motive force lost in the line is ςc, which must be equal to the difference of electro-motive forces at the terminals of generator and motor

$$E_t = \varsigma c + e_t.$$

The internal electrical energy of the generator is $c\ E_a$, that of the motor is $c\ e_a$, and the proportion between the two is the electrical efficiency of the whole system.

$$\text{Electrical efficiency} = \frac{e_a}{E_a}.$$

By combining this expression with the above equations we find also: Electrical efficiency

$$= \frac{e_a}{e_a + c\,(\varsigma + r_a + r_m + R_a + R_m)} \quad \ldots \quad 31).$$

It is evident that whatever may be the resistance of the line ς, or in other words whatever may be the distance to which the energy has to be transmitted, we can always obtain the same electrical efficiency by suitably varying c and e_a. The higher e_a, the counter-electro-motive force of the motor, the greater is the electrical efficiency. Now there are two means by which we can raise the counter-electro-motive force. The one is by increasing the speed, the other by employing machines containing a large number of turns of wire (Nt) on their armatures. The first expedient is limited by the mechanical difficulties generally attendant on the use of excessive speeds, and the latter by the difficulty that the internal resistance of the machines is the greater the more turns of wire they contain. This, in itself, would not affect the result if the electro-motive force would increase in the same proportion as the resistance of the machine. But this is not the case. If a given size armature core be wound with many turns of fine wire, and a precisely similar core with such a number of turns of stouter wire, that both windings fill exactly the same space, the weight of copper contained in the armature wound with stout wire must always be somewhat greater than in the other, because the space wasted by the insulating covering on the wire is less. It is clearly not admissible to reduce the thickness of insulation in the same ratio as the gauge of the wire. A minimum thickness is absolutely necessary for the safe handling during the process of manufacture, and moreover the finer

wire is intended for an armature of higher electro-motive force and should for this reason alone have rather better insulation than the thick wire, which is intended for a lower electro-motive force. A good practical rule is to employ a covering of cotton about 6 mils for wires of all sizes up to about 120 mils. The diameter of the covered wire is thus by 12 mils greater than that of the single wire. Now it can be shown that the energy wasted in heating the wire of the armature is inversely proportional to the weight of copper employed, and therefore, with the armature of stouter wire, the same electrical output can be obtained at a smaller cost of energy wasted in heating the wire. The same holds good for the field magnet coils. The dynamo wound with stouter wire will, therefore, be the most economical of the two, as its internal resistance will be relatively small as compared to its electro-motive force. Inversely, if we wind the machines (generator and motor) with very fine wire in order to obtain a high electro-motive force, we increase their resistances, r_a, r_m, R_a, R_m, in a somewhat quicker ratio, and thus lower their efficiency, taken apart from the line. As regards the line resistance ς, the higher the electro-motive force the better, and it will be evident that taking these two things into consideration there must be one particular value for the electro-motive force for which the electrical efficiency becomes a maximum. This value can be found in each given case by assuming different windings for generator and motor, and calculating their electro-motive forces and resistances. By inserting the data thus obtained successively into equation 31) it can easily be seen which is the best. We suppose that the resistance of the line is given. The electrical data thus obtained can only be regarded as a first approximation to a solution of the problem, be-

cause they were obtained on the basis of the highest electrical efficiency, whereas the question of importance is the actual or commercial efficiency. It is sometimes assumed that the commercial efficiency of dynamos and motors bears a fixed proportion to their electrical efficiency, and if that were so we could obtain the actual efficiency of our system of transmission by multiplying equation 31) with that fixed proportion. But this would not be correct. It is evident that the commercial efficiency of a motor cannot be a fixed quantity, but must depend on the power given out, being, generally speaking, the higher the nearer the work done by the motor approaches to the maximum for which it is designed. This relation is best expressed in the manner adopted in Chapter V., by assuming that a certain minimum of current, γ, is necessary to overcome the mechanical and magnetic friction of the motor, and that all the power corresponding to the difference between this minimum and the actual working current is available for external work. Similarly we assume that a certain minimum of current, g, multiplied by the internal electro-motive force of the generator, represents the mechanical energy absorbed by mechanical and magnetic friction. We have, therefore, the following relations:

GENERATOR.

$$\text{Work absorbed, } W = (c + g)\, E_a.$$

MOTOR.

$$\text{Work given out, } w = (c - \gamma)\, e_a.$$

Put $R_a + R_m = R$, and $r_a + r_m = r$, then for series-wound generator and motor we have

$$E_a = e_a + c\,(\varsigma + R + r),$$
$$W = (c + g)\,(e_a + c\,(\varsigma + R + r))$$

And the commercial efficiency of the whole system is

$$\eta = \left(\frac{c - \gamma}{c + g}\right) \frac{e_a}{E_a}$$

$$\eta = \left(\frac{c - \gamma}{c + g}\right) \frac{e_a}{e_a + c\,(\varsigma + R + r)} \quad . \; . \; . \; . \; . \; 32).$$

A question of practical importance is that concerning the working conditions under which, in a given system of transmission, the commercial efficiency becomes a maximum. As already shown, the first condition for attaining this object is to work the generator at as high a speed as mechanically safe. We shall therefore assume that its electro-motive force E_a is a constant and as high as possible. The variables are the current c, and the counter-electro-motive force e_a of the motor. If we allow the motor to run too slowly it will allow a large current to pass, but this will entail a considerable waste of energy in heating the line and the two machines. If we speed the motor too high, this waste will be very small, but the high counter-electro-motive force will only allow very little current to pass, and in this case the work done by the motor will be small, thus again lowering the commercial efficiency. Between these two extreme cases there must evidently exist one current and one counter-electro-motive force for which the commercial efficiency becomes a maximum. To find thesė values we form the first differential quotient and equal it to zero. Thus the most favourable current will be found by the equation

$$\frac{d\eta}{dc} = o,$$

and the most favourable counter-electro-motive force will be found by the equation $\frac{d\eta}{d\,e_a} = o.$

Writing for the sake of brevity E for E_a, and e for e_a, and R for the sum of the resistances $\varsigma + R + r$, the first equation gives,

$$(c + g)(E - 2 R c + \gamma R) - c(E + \gamma R) + R c^2 + \gamma E = o,$$

c being the only unknown quantity. Resolving the equation we find

$$c = -g - \sqrt{g^2 + \frac{E}{R}(g + \gamma) + \gamma g} \quad \ldots\ldots \quad 33).$$

It will be seen that the quadratic equation has two roots or values for c, the one being positive the other negative. The latter implies that the current travels in the opposite direction, in which case the motor would become the generator and *vice versâ*. This does not concern us here, as it applies to cases where the receiving machine is larger than the generating dynamo, an arrangement which no practical engineer would employ. We have, therefore, only to deal with the positive root, viz.,

$$c = -g + \sqrt{g^2 + \frac{E}{R}(g + \gamma) + \gamma g} \quad \ldots\ldots \quad 34).$$

Having thus determined c, we find the counter-electromotive force of the motor,

$$e = E - Rc \quad \ldots\ldots\ldots\ldots \quad 35).$$

To obtain a maximum of commercial efficiency the motor must be so speeded that its counter-electro-motive force attains the value $E - Rc$.

By using the equation $\frac{d\eta}{de} = o$, we can also obtain directly the most favourable counter-electro-motive force. The solution gives again two values for e, one smaller

than E, the other larger than E. The latter corresponds to the case when motor and generator have changed places and need not be further considered for reasons above stated. The former value for e is alone of importance ; it is given by the formula,

$$e = E + Rg - \sqrt{(E+Rg)^2 - (E + Rg)(E - R\gamma)} \quad 36)$$

This equation does not clearly show that e must in all cases be smaller than E, but on developing the expression under the square root on the right, we also obtain,

$$e = E + Rg - \sqrt{R^2 g^2 + R^2 g \gamma + E R (g + \gamma)} \quad . \quad 37)$$

The same expression is obtained by inserting,

$$c = \frac{E - e}{R}$$

into formula 34).

It is evident that the square root in 37) must under all circumstances be numerically greater than $R\,g$, and therefore e must under all circumstances be smaller than E. Now, according to the orthodox theory found in text books, maximum efficiency is obtained for $E = e$. This could only be if $g = o$ and $\gamma = o$; that is to say, if the dynamo would absorb no energy whatever when working an open circuit and if the motor could be kept running idle without the expenditure of electrical energy. Both these conditions are evidently absurd.

Since the formulas 32) to 37) have a somewhat complicated appearance, it might be as well to elucidate their application by a practical example. We will assume that in a given system of transmission the generator can be worked at the safe limit of 1,000 volts and 20 amperes, and under these conditions has a commercial efficiency of 80°/₀. Its internal resistance is 5 ohms. Its external

lectro-motive force at maximum output would there-
re be

$$1{,}000 - 20 \times 5 = 900 \text{ volts.}$$

To produce 900 volts and 20 amperes with a machine aving 80°/₀ efficiency, requires the expenditure of $8{,}000 \times \frac{100}{80} = 22{,}500$ watts. Of this amount 20,000 ratts represents the internal electrical energy developed in he armature, and 2,500 watts represents the energy ne-essary to overcome the mechanical and magnetic friction f the dynamo. At 1,000 volts this energy is represented y a current of 2·5 amperes. A similar calculation pplied to the motor gives, say, 1·5 amperes. We have, herefore,

$$g = 2{\cdot}5 \qquad\qquad \gamma = 1{\cdot}5.$$

Let us assume the distance between generator and motor o be one mile, and the circuit to consist of two miles of opper wire ·134 inch in diameter. At 98 per cent. con-luctivity the resistance of the line would therefore be ·2 ohms. Allowing 3 ohms for the resistance of the hotor, we have

$$R = 14{\cdot}2.$$

These are all the data necessary for solving the problem s to current and counter-electro-motive force for maxi-num efficiency. Equation 34) gives immediately

$$c = 14{\cdot}5 \text{ amperes,}$$

nd 35) or 36) gives

$$e = 790 \text{ volts.}$$

The maximum commercial efficiency attainable under hese conditions is from equation 32)

$$\eta = \frac{14{\cdot}5 - 1{\cdot}5}{14{\cdot}5 + 2{\cdot}5} \; \frac{790}{1{,}000} = 60 \text{ per cent.}$$

Assuming then that the generator be kept running at such a speed, that its electro-motive force is kept at the safe limit of 1,000 volts, we must, in order to obtain the maximum possible return of 60 per cent. of the power expended, so gear and speed the motor that it will oppose an electro-motive force of 790 volts to the current. The strength of the latter will then be 14·5 amperes, and the energy actually given out by the motor will be $\frac{790}{746}(14{\cdot}5 - 1{\cdot}5) = 13{\cdot}8$ horse-power.

To show how a departure from these conditions affects the efficiency and power developed, the following table is added :—

Counter Electro-motive Force.	Current.	Commercial Efficiency, per cent.	Power obtained from motor, H. P.
790	14·5	60	14
876	8	54	7·7
716	20	58·6	18

A glance at this table will show that for currents either larger or smaller than 14·5 amperes, the efficiency is less than 60 per cent., but that the falling off is limited to a few per cent., whereas the power transmitted may vary considerably. This is a very valuable property of electric transmission of energy, as it allows a variation of power between wide limits, without serious sacrifice of efficiency, and thus renders the system very elastic. The great importance of this point will become apparent when we compare electric with hydraulic transmission. In the latter the motor consumes always the same quantity of water, whatever work it be doing ; and since the pressure is constant, the efficiency falls very low if the motor is working under its normal power. To remedy this, Mr.

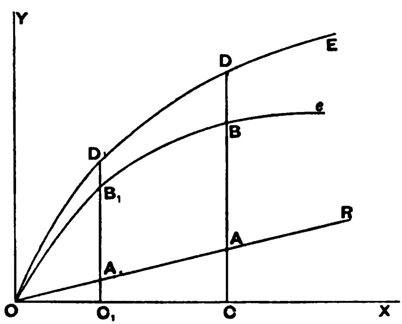
Hastie has introduced a water-motor with variable crank-radius, the latter being automatically adjusted to the work done by a spring. A contrivance of this nature, although extremely ingenious, adds considerably to the cost and complication of the machine and represents an additional chance of break-down. On the other hand, electricity can be used without any separate contrivance for regulation, and has thus a great advantage over hydraulic transmission.

The system of transmitting energy by means of two series-wound dynamos has the other advantage of being almost perfectly self-regulating as regards the speed of the motor. This is a point which has as yet received hardly any attention from writers on the subject, and therefore a somewhat detailed explanation of this valuable property in this place will be opportune.

It has been shown how a motor intended to be worked by a constant current can be made self-regulating, that is, can be arranged to run always at the same predetermined speed, whatever load may be thrown on it. It has also been shown how motors can be made self-regulating, if supplied with current at constant pressure. In the first case, the electro-motive force must increase as the load increases ; and, in the second place, the current must increase as the load increases, one or the other being kept automatically constant at the generating station. But with a series-wound dynamo, neither the current nor the electro-motive force are constant, but vary in a certain dependence on each other. It might thus, at first sight, seem as if the problem of making the motor self-regulating were thereby rendered very much more difficult. This is not the case. The evil, if we may so regard it, in the dynamo becomes of itself the remedy in the motor.

Let, in Fig. 67, *O E* represent the ordinary characteristic of the series-wound generator, the curve being drawn for a constant speed of, say, 1,000 revolutions a minute. Let *O e* represent the characteristic of the motor also for the speed of, say, 1,000 revolutions. The counter-electro-motive force developed in the armature of the motor at that speed is therefore represented by the ordinates of the curve *O e*. Thus to a current *O C* will be opposed an electro-motive force *C B*, to a current $O\ C^1$ will be opposed an electro-motive force $C_1\ B_1$, and

Fig. 67.



so on. In the dynamo the electro-motive force corresponding to the current *O C* is *C D*, and that corresponding to the current $O\ C_1$ is $C_1\ D_1$. Draw *O R* under such an inclination to the horizontal that the tangent of the angle *R O X* represents to the scale of the diagram the numerical value of the sum of the resistances $(R + r + \varsigma)$ of dynamo, motor, and line, then the electro-motive force lost in overcoming these. resistances is for the current *O C*, evidently *C A*, for the current $O\ C_1$, $C_1\ A_1$, and so on. The ordinates between the straight line *O R* and the characteristic curve *O E* represent, therefore, the counter-electro-motive forces which must be developed in

the armature of the motor at various currents. If the current is $O\ C$, the counter-electro-motive force is $A\ D$, if the current is $O\ C_1$ the counter-electro-motive force is $A_1\ D_1$, and so on. Now the counter-electro-motive force of the motor, if running at a constant speed of 1,000 revolutions a minute, is given by the curve $O\ e$, and it will be seen that if the ordinates of this curve are for every current equal to the ordinates contained between $O\ R$ and $O\ E$, then the motor suits perfectly the requirements of the generator, and it will run at a constant speed. The motor will run at that speed whether the current be $O\ C_1$ or $O\ C$, provided that $C_1\ A_1 = B_1\ D_1$, and $C\ A = B\ D$.

The solution of the problem consists, therefore, in the proper choice of motor and dynamo, so that their characteristics fit each other as near as possible, as explained. Beyond this, no other precaution or apparatus is necessary to make the system perfectly self-regulating. Even if the characteristics should not fulfil the condition $C\ A = B\ D$ over their entire range, it will, as a rule, not be difficult to find two points, C_1 and C, tolerably far apart, for which the condition is fulfilled, and between which the deviation of one curve from the form demanded by the other is very trifling. The system will, therefore, be practically self-regulating between these limits. Two years ago the author has had occasion to practically test the soundness of this theory. He had occasion to use electric transmission of energy within the limits of an engineering works, for the purpose of supplying with power the pattern-makers' shop, which on account of its location could not be reached by any mechanical transmission. The power required by the wood-working machines in that shop, including band and circular saws, was, of course, very variable, and it became a matter of

the greatest importance to keep the main shaft—from which the different tools were worked by belting—revolving at a constant speed. This object was attained by the method just described. The generator was a Bürgin dynamo, driven at a constant speed from the main engine in another part of the works, and the motor was also a Bürgin dynamo, but wound for a lower electro-motive force. There was a considerable distance between the two characteristics $O\ E$ and $O\ e$, Fig. 68, and to find two points, $O\ C_1$ and $O\ C$, for which the condition $C\ A = B\ D$ should be fulfilled, it was necessary to increase the inclination of the line $O\ R$ by placing a little additional resistance into the circuit. This, of course, entailed some small loss of energy, but was in no way a fault of the system. It was occasioned simply by the necessity of using the two dynamos which happened to be at hand. If the machines could have been designed for this very purpose, no additional resistance would have been required, and the automatic regulation would have been equally good.

CHAPTER VII.

The Line—Relation between Capital Outlay and Waste of Energy—Most Economical Size of Conductor—Formula for Maximum Current—Formula for Mean Current—Tables for Finding Most Economical Size—Heating of Conductor—Table for Rise of Temperature.

BOTH as regards first cost and economy of working, the line forms a very important item in any extended system of electric transmission of energy. We have to consider two separate cases. The one, where energy from a central station is transmitted to and divided between a number of small working centres all grafted upon a network of conductors forming the main circuit, and the other, where all the energy is conveyed to a single receiving station along a pair of conductors without any ramifications. The first case would occur in a system of town supply where electricity is furnished for lighting and power purposes, and where the lamps and motors are all connected in parallel to the mains. The second is that occurring when energy from an hitherto inaccessible source is conveyed to a convenient point of application, the distance being considerable. Whatever particular form of transmission and distribution the system may have, it will be clear that the first cost of the conductors, and the annual expenditure represented by the energy wasted in heating the conductors, follow opposite laws. To economize energy it is necessary to employ leads of low resistance, and, therefore, of considerable cross-sec-

tional area. To reduce the first cost we would, on the other hand, employ leads of small weight—that is, of small sectional area. We see that first cost and the subsequent working expenses are both governed by the area of conductor chosen, but whilst the former increases with the area, the latter decreases as the area increases, and it is evident that in each system of electric transmission of energy there must exist at least one particular area of conductor for which the sum of interest on its first cost, and annual cost of energy wasted, becomes a minimum. It is also evident that, notwithstanding any other consideration, this particular size of conductor must be adopted, being the cheapest in the long run.

The determination of this most economical size of conductor is somewhat complicated, and must be made specially for each case, regard being had to the following: 1. The rate of interest to be charged on capital outlay; 2. The cost of one horse-power-hour at the terminals of the generator; 3. The number of hours per annum that the maximum energy is required, and the number of hours that three-fourths, one half, and one quarter this amount is required; 4. The cost of unit weight of the conducting material; 5. The cost of insulation; 6. The cost of supports if an overhead line, or troughs if an underground line; 7. The cost of labour in laying. If it were permissible to consider the capital outlay as proportional to the total weight of conducting material, then for a given line we have the relation $p\,K = k\,a\,p$, where K is the total cost of the line, k a constant and p the annual rate of interest. The resistance of the line is inversely proportional to the area a, and the energy wasted equals resistance multiplied by the square of the current. Let q represent the cost of one electrical horse-

power-hour at the terminals of the dynamo, and let t represent the number of hours per annum during which the current c is flowing—there being always the full amount of energy transmitted—then we have the annual value of energy wasted,

$$W = \frac{w}{a} q t c^2$$

w being a constant. The total expenditure will be a minimum if $\frac{d K p}{d a} + \frac{d W}{d a} = o.$

This gives $p K = \frac{w q t c^2}{a^2}$, and

$$a = c \sqrt{\frac{w q t}{p k}}.$$

By inserting this value into the equations for K and W we find

$$p K = c \sqrt{w q t k p} \text{ and}$$
$$W = c \sqrt{w q t k p}$$

Hence $\qquad p K = W,$

or the most economical area of conductor, will be that for which the annual interest on capital outlay equals the annual cost of energy wasted. This law is commonly known as Sir William Thomson's law, and was first published by him in a paper on "The Economy of Metal Conductors of Electricity," read before the British Association in 1881. It should be remembered that this law in the form here given only applies to cases where the capital outlay is strictly proportional to the weight of metal contained in the conductor. In practice this is, however, seldom correct. If we have an underground cable, the cost of digging the trench and filling in again will be the same whether the cross-sectional area of the

cable be half a square inch or one square inch or more; and other items, such as insulating material, are if not quite independent of the area, at least dependent in a lesser degree than assumed in the formula. In an overhead line we may vary the thickness of the wire within fairly wide limits without having to alter the number of supports, and thus there is here also a certain portion of the capital outlay which does not depend on the area of the conductor. It would, therefore, be more correct to write

$$K = Ko + ka,$$

where Ko represents that part of the capital outlay which is constant and independent of the area of the conductor. This addition on the right-hand side of the formula makes no alteration in the differential equation, for $\frac{d\,Ko}{d\,a} = o.$

We obtain, therefore, again,

$$a = c\sqrt{\frac{w\,q\,t}{p\,k}},$$

but the value of $p\,K$ is altered.

$$p\,K = p\,Ko + c\sqrt{w\,q\,t\,k\,p}$$
$$W = c\sqrt{w\,q\,t\,k\,p}.$$

The interest on capital outlay, and the annual cost of energy wasted are now in the relation

$$p\,K = p\,Ko + W.$$

They are no longer equal, but the interest on capital outlay must be greater than the annual cost of energy wasted. By writing the above equation in the form

$$p\,(K - Ko) = W,$$

we find that the most economical area of conductor is that

for which the annual cost of energy wasted is equal to the annual interest on that portion of the capital outlay which can be considered to be proportional to the weight of metal used.

Professor George Forbes, in his Cantor Lecture, on "The Distribution of Electricity," delivered at the Society of Arts, in 1885, called that portion of the capital outlay which is proportional to the weight of metal used, "The Cost of Laying One Additional Ton of Copper," and he showed that for a given rate of interest inclusive of depreciation, and a given cost of copper the most economical section of the conductor is independent of the electro-motive force and of the distance, and is proportional to the current. These facts can also be seen from the above formula

$$a = c\sqrt{\frac{w\,q\,t}{p\,k}},$$

since the square root is a constant for each case, and since neither distance nor electro-motive force appear in the expression for a, which is simply proportional to c.

Having in a given system of electric transmission settled what current is to be used, we can, by the aid of Sir William Thomson's law, proceed to determine the most economical size of conductor. To do this we must know the annual cost of an electrical horse-power inclusive of interest and depreciation on the building, prime mover, and dynamo, we must know what is the cost of laying one additional ton of copper, and we must settle in our mind what interest and depreciation shall be charged to the line. These points will serve to determine the constants of our formulas, and then the calculation can easily be made. To avoid the labour of going through these

figures for every special case, Professor Forbes has prepared and published in his Cantor Lectures, some extremely useful tables which are reproduced on pages 185 and 186. Table A refers to the cross-sectional area of conductor required to carry a current of 1,000 amperes if the annual cost of one electrical horse-power varies from £5 to £20. Table B refers to the cost of laying one additional ton of copper, and interest and depreciation on it. The use of the tables will best be seen by an example. Say we have to transmit 50 amperes, the annual value of one horse-power is £10, and the cost of the line is £110 per ton of copper plus a constant. We shall also assume that it has been decided to charge $7\frac{1}{2}$ °/₀ for interest and depreciation on the line. We look in Table B horizontally along the line opposite $7\frac{1}{2}$ till we come to the vertical column headed £110. We find thus the figure ·424. We now look in Table A horizontally along the line opposite £10 until we find again ·424 or the nearest figures to it. In the present case ·441 and ·411. The heading of the vertical column corresponding to this figure gives the area of conductor necessary for 1,000 amperes. We find thus that the conductor should be between 2·8 and 2·9 square inches—say average 2·85. But since our current is 50 and not 1,000 amperes, the area of conductor will have to be $\frac{50}{1,000} \times 2{\cdot}85 = {\cdot}1325$ square inches. If we were to adopt a larger conductor the system would be less economical, because the capital outlay would become too great, and if we were to adopt a smaller conductor the system would be less economical because the waste of energy would be too great.

TABLE A.—*Section per Thousand Amperes in Inches.*

—	1	1·1	1·2	1·3	1·4	1·5	1·6	1·7	1·8	1·9	2
Annual Cost of Electrical Horse-power. £											
5	1·628	1·356	1·147	·980	·857	·746	·658	·585	·523	·471	·426
6	1·954	1·627	1·377	1·176	1·028	·895	·790	·702	·628	·565	·511
7	2·279	1·898	1·606	1·372	1·199	1·044	·921	·819	·733	·660	·596
8	2·605	2·169	1·836	1·568	1·370	1·194	1·053	·936	·838	·754	·682
9	2·930	2·441	2·065	1·764	1·542	1·343	1·185	1·053	·942	·848	·767
10	3·256	2·712	2·295	1·960	1·713	1·492	1·316	1·170	1·047	·942	·852
11		2·983	2·524	2·156	1·885	1·641	1·448	1·287	1·152	1·037	·937
12			2·754	2·352	2·056	1·790	1·580	1·404	1·256	1·131	1·022
13				2·548	2·227	1·940	1·711	1·521	1·361	1·225	1·108
14					2·398	2·089	1·843	1·638	1·466	1·319	1·193
15						2·238	1·975	1·755	1·570	1·414	1·278
16							2·106	1·872	1·675	1·508	1·363
17								1·990	1·780	1·602	1·448
18									1·884	1·696	1·534
19										1·790	1·619
20											1·704

—	2·1	2·2	2·3	2·4	2·5	2·6	2·7	2·8	2·9	3·0	3·1	3·2
Annual Cost of Electrical Horse-power. £												
5	·386	·355	·324	·298	·276	·255	·237	·221	·206	·192	·180	·170
6	·463	·426	·389	·358	·331	·305	·284	·265	·247	·230	·216	·203
7	·540	·498	·454	·417	·386	·356	·331	·309	·288	·269	·252	·237
8	·618	·569	·518	·477	·442	·407	·378	·353	·329	·307	·288	·271
9	·695	·640	·583	·536	·497	·458	·426	·397	·370	·346	·324	·305
10	·772	·711	·648	·596	·552	·509	·473	·441	·411	·384	·360	·339
11	·849	·782	·712	·656	·607	·560	·520	·485	·452	·422	·396	·373
12	·926	·853	·778	·715	·602	·611	·568	·529	·493	·461	·432	·407
13	1·004	·924	·842	·775	·718	·662	·615	·573	·534	·499	·468	·440
14	1·081	·995	·907	·834	·773	·713	·662	·617	·575	·538	·504	·475
15	1·158	1·066	·972	·894	·828	·764	·710	·662	·617	·576	·540	·509
16	1·235	1·137	1·037	·954	·883	·814	·757	·706	·658	·614	·576	·542
17	1·312	1·208	1·102	1·013	·938	·865	·804	·750	·699	·653	·612	·576
18	1·390	1·279	1·166	1·073	·994	·916	·851	·794	·740	·691	·648	·610
19	1·467	1·351	1·231	1·132	1·049	·967	·899	·838	·781	·730	·684	·644
20	1·544	1·413	1·296	1·192	1·104	1·018	·946	·882	·882	·768	·720	·678

—	3·3	3·4	3·5	3·6	3·7	3·8	3·9	4	4·5	5·0	5·5	6·0
Annual Cost of Electrical Horse-power. £												
5	·160	·150										
6	·192	·180	·170									
7	·224	·210	·199	·188								
8	·256	·240	·227	·215	·203							
9	·288	·270	·256	·242	·229	·217						
10	·320	·300	·284	·269	·254	·241	·229					
11	·352	·330	·312	·296	·279	·265	·252	·240				
12	·384	·360	·341	·323	·305	·289	·275	·262	·206			
13	·416	·390	·369	·350	·330	·313	·298	·283	·224	·181		
14	·448	·420	·398	·379	·356	·337	·321	·305	·241	·195	·162	
15	·480	·450	·426	·404	·381	·362	·344	·327	·258	·209	·174	·147
16	·512	·480	·454	·430	·406	·386	·366	·349	·275	·223	·186	·156
17	·544	·510	·483	·457	·432	·410	·389	·371	·292	·237	·199	·166
18	·576	·540	·511	·484	·457	·434	·412	·392	·310	·251	·209	·176
19	·608	·570	·540	·511	·483	·458	·435	·414	·327	·265	·220	·186
20	·640	·600	·568	·538	·508	·482	·458	·436	·344	·279	·232	·196

TABLE B.—*Cost of Laying one additional Ton of Copper.*

—		£60	£65	£70	£75	£80	£85	£90	£95	£100	£110	£120
Percentage allowed for interest and depreciation per annum.	5	·154	·167	·180	·193	·206	·219	·231	·244	·257	·283	·309
	7½	·231	·251	·270	·289	·309	·328	·347	·366	·386	·424	·463
	10	·308	·334	·360	·386	·411	·437	·462	·488	·514	·565	·617
	12½	·385	·418	·450	·482	·515	·546	·578	·610	·643	·707	·772
	15	·463	·501	·540	·578	·617	·656	·694	·733	·771	·849	·926
	20	·616	·668	·720	·771	·824	·875	·925	·976	1·029	1·131	1·235
	25	·771	·835	·900	·964	1·028	1·093	1·156	1·221	1·285	1·415	1·543

—		£130	£140	£150	£200	£250	£300	£350	£400	£450	£500
Percentage allowed for interest and depreciation per annum.	5	·334	·360	·385	·514	·643	·772	·900	1·029	1·157	1·286
	7½	·501	·540	·579	·771	·964	1·157	1·350	1·543	1·736	1·929
	10	·668	·720	·770	1·029	1·286	1·543	1·800	2·057	2·315	2·571
	12½	·835	·900	·964	1·285	1·607	1·929	2·250	2·572	2·893	3·205
	15	1·003	1·080	1·155	1·543	1·928	2·314	2·700	3·086	3·471	3·857
	20	1·336	1·440	1·540	2·056	2·571	3·089	3·600	4·115	4·629	5·144
	25	1·671	1·800	1·925	2·572	3·125	3·857	4·500	5·143	5·786	6·430

We have calculated the area of our conductor under the supposition that the maximum current of 50 amperes would be flowing during all the hours per annum that the installation is at work. In other words, we have assumed that the motor when at work should always give full power. This will, in practice, seldom be the case. Whether we want the motor for propelling railway cars, or producing the electric light, or working lathes and other tools generally, or giving power for a whole mill, the amount of energy required at various times will be different. It has been shown that energy can be transmitted in either of three ways. First, by keeping the current constant and varying the electro-motive force of the generator in accordance with the demand for power at the receiving station. Secondly, by keeping the electro-motive force constant, and varying the current in accordance with the demand for power. Thirdly, by

arying both current and electro-motive force. In the rst case, where the current is constant, the above forıula for the most economical area of conductor is at once pplicable whatever may be the difference in the energy ransmitted at various times of the day or year. In the wo other cases, however, a correction must be applied to he formula in order that account may be taken of those ours when a reduced current is passing, and when the nost economical area of conductor would be smaller than hat corresponding to the full current and maximum nergy transmitted. This correction must evidently be pplied in this form:—We make our calculation not for he full current but for the reduced current, the reduction eing the greater the greater is the number of hours luring which a reduced current is passing as compared o the number of hours during which the full current is passing. At first sight it might seem as if this reduced r mean current could be determined by simply dividing he total number of ampere hours per annum by the number of hours per annum. This would, however, not be correct, for the reason that the energy wasted varies not with the current itself, but with the square of the current. Let t_1, t_2, t_3, t_4, represent the number of hours per annum luring which one quarter, one half, three quarters of the full current, and the full current is respectively passing hrough the conductor; then the total horse-power hours wasted per annum is evidently

$$W = \frac{w}{a}\, q \left(\left(\frac{c}{4}\right)^2 t_1 + \left(\frac{c}{2}\right)^2 t_2 + \left(\frac{3}{4}\, c\right)^2 t_3 + c^2 t_4 \right).$$

To find that mean current, c_m, which flowing during

$$t = t_1 + t_2 + t_3 + t_4$$

hours per annum will cause an equal waste of energy, we put

$$\frac{w\,q}{a}\,c_m^2\,t = W,$$

and obtain

$$c_m = c\sqrt{\frac{\left(\frac{1}{4}\right)^2 t_1 + \left(\frac{1}{2}\right)^2 t_2 + \left(\frac{3}{4}\right)^2 t_3 + t_4.}{t_1 + t_2 + t_3 + t_4.}}$$

This value of the mean current, c_m, must be used in the determination of the size of conductor in order that the annual cost of energy wasted and the interest and depreciation on that part of the capital outlay which is proportional to the weight of conductor used should be equal.

To facilitate the calculation Professor Forbes gives the following table :—

t_1.	t_2.	t_3.	t_4.	Ratio.
0	0	0	1	1·000
0	1	0	1	0·790
1	0	2	1	0·744
1	1	1	1	0·685
2	2	1	1	0·604
4	0	0	1	0·500

The figures in the column headed "Ratio" are those with which the most economical area for the maximum current must be multiplied to obtain the most economical area for a varying current. In our previous example we found that the conductor should be ·1325 square inches, provided that the full current of 50 amperes be always

flowing. Say that our transmission will be at work 4,000 hours per annum, but that the full current will only flow for 1,000 hours, the remaining 3,000 hours being equally divided between quarter current, half current, and three-quarter current. In this case $t_1 = 1$, $t_2 = 1$, $t_3 = 1$ and $t_4 = 1$; and we see from the fourth line in the table that the area of our conductor must be reduced to ·685 of the area for full current. We should, therefore, have to employ a conductor of ·0907 square inches area, or say a wire ·34 inches in diameter.

The heat generated in the conductor by the passage of the current must be carried away in the same measure as it is generated, if the temperature of the conductor is to remain at a safe limit. An undue increase of temperature is objectionable for three reasons. In the first place it spoils the insulation, reducing the insulating power of the material and rendering it so soft as to allow the conductor to sink through it. This is a very important point, and should be guarded against with great care. It has been proposed to lay underground cables in iron troughs, completely filled with a bituminous compound, in which the cables are to be imbedded. This arrangement would serve excellently well for keeping the cables dry, but it has the great drawback that any compound of that nature does not behave as a rigid body, but rather as a very thick fluid. It is well known that a stick of sealing wax fastened by strings to a card which is suspended vertically, will in course of time bend as if it were a flexible ribbon, and the strings will cut through it. This process goes on even in a cold room, but is accelerated by heat. Now in our underground conductor some amount of heat is always developed, and if we trust the bituminous compound to support the cables we shall find them, after a certain time,

at the bottom of the trough, and short circuits will become very probable. The second reason why an increase of temperature is objectionable is, that the resistance of the cable becomes greater, causing an additional waste of energy. The third reason is that an undue increase of temperature may in an overhead line actually cause a fire risk at the points where the cables are attached to buildings, and may in an underground line become very unpleasant to foot passengers.

It becomes thus a matter of great importance to determine beforehand what rise in temperature is to be expected in each given case, and if that rise should be found to be greater than appears safe, provision must be made to increase the rate at which heat is carried off. This can generally be done by increasing the superficial area of the conductor. Say we have one circular conductor of 1 square inch area, and find that with 1,000 amperes flowing it would become too hot. Now by splitting up this conductor into 10 separate wires each one-tenth of a square inch cross-sectional area we have not altered the total amount of energy transformed into heat, but we have increased the surface exposed to the cooling action of the surrounding air in the ratio of $1 : \sqrt{10}$, and therefore the ten thin wires can dissipate more than three times the heat, as compared with the single thick wire. Professor Forbes gives a table—reproduced on page 191—from which it can be seen at a glance what current a wire can carry when the rise in temperature is 9° and 26° above that of the surrounding air.

Carrying capacity and heating of Wires.

B. W. G.	Diameter in inches.	Section in square inches.	lb. copper per 100 yards.	Resistance per 100 yards at 15·5° C., or 60° F.		Wire heated to 9° above temp. of air.		Wire heated to 26° above temp. of air.	
				B. A. Units.	Legal Ohms.	Current.	Loss in Volts per 100 yds.	Current.	Loss in Volts per 100 yds.
	2·26	4·0	4608·	·000634	·000627	1514·	·998	2490·	1·730
	2·11	3·5	4032·	·000724	·000716	1384·	1·042	2246·	1·783
	1·95	3·0	3456·	·000845	·000835	1228·	1·079	1995·	1·847
	1·78	2·5	2880·	·00101	·000999	1072·	1·125	1739·	1·931
	1·60	2·0	2304·	·00127	·00126	913·	1·205	1482·	2·059
	1·38	1·5	1728·	·00163	·00161	732·	1·288	1188·	2·187
	1·13	1·0000	1152·	·00253	·00250	542·1	1·426	880·0	2·446
	1·00	·7854	904·78	·00326	·00324	451·5	1·513	732·7	2·586
	·75	·44178	508·93	·00584	·00578	293·0	1·746	475·5	2·991
	·707	·39250	452·16	·00653	·00651	268·0	1·800	435·2	3·081
	·500	·19635	226·18	·01307	·01292	159·4	2·139	258·6	3·659
0000	·454	·1618	186·39	·01567	·01550	138·1	2·248	224·1	3·854
000	·425	·1419	163·47	·01786	·01766	125·1	2·323	203·0	3·977
00	·380	·1134	130·64	·02236	·02211	105·7	2·456	171·4	4·201
	·354	·09842	113·37	·02605	·02576	95·1	2·546	154·3	4·357
0	·340	·09079	104·60	·02824	·02793	89·4	2·594	145·1	4·442
1	·300	·07068	81·42	·03637	·03597	74·0	2·755	120·1	4·722
2	·284	·06334	73·00	·04048	·04003	68·63	2·850	114·4	4·880
3	·259	·05268	68·68	·04867	·04823	59·60	2·981	96·7	5·102
4	·238	·04448	51·61	·05764	·05700	52·37	3·102	85·0	5·315
5	·220	·03801	43·78	·06740	·06665	46·5	3·213	75·5	5·521
6	·203	·03236	37·27	·07937	·07849	41·27	3·360	66·97	5·762
7	·180	·02544	29·3	·1006	·08943	34·31	3·553	55·69	6·084
8	·165	·02138	24·62	·1199	·11857	30·25	3·728	49·09	6·384
9	·148	·01720	19·81	·1492	·14643	25·28	3·878	41·03	6·630
10	·134	·014102	16·25	·1812	·17919	22·12	4·133	35·90	7·075
11	·120	·011309	13·00	·2267	·22418	18·74	4·366	30·41	7·473
12	·109	·009331	10·74	·2748	·27175	16·25	4·589	26·38	7·857
13	·095	·007088	8·16	·3617	·35769	13·09	4·866	21·25	8·332
14	·083	·005410	6·23	·4739	·47064	10·84	5·280	17·58	9·031
15	·072	·004071	4·68	·6298	·62281	8·723	4·646	14·14	9·652
16	·065	·003318	3·82	·7727	·76412	7·481	5·931	12·14	10·169
17	·058	·002642	3·04	·9711	·96032	6·371	6·354	10·24	10·771
18	·049	·001885	2·07	1·3596	1·3447	4·876	6·813	7·95	11·691
19	·042	·0013854	1·60	1·8502	1.8297	3·883	7·385	6·31	12·658
20	·035	·0009621	1·108	2·6650	2·6354	2·953	8·087	4·80	13·866

Legal volts 96 per cent. conductivity copper. Heating of bare copper wire, emissivity = ·00025 C.G.S. units.

CHAPTER VIII.

Circuits for Electric Transmission—Circuits for Electric Distribution—Relative Importance of Insulation—Aërial Lines—Insulators—Attachment of Conductor to Insulator—Joints—Couplings—Material for Aërial Lines—Estimate for Aërial Line—Protection from Lightning—Underground Lines—Edison Mains—The Three-Wire System—Various Systems of Underground Conduits—Lead-Covered Cables.

THE question whether the line should be carried overhead or be placed underground, depends on a number of local circumstances, but as a rule it will be more economical and sufficiently safe to use aërial conductors for the transmission proper of energy, whereas for its distribution underground cables are preferable, and in some cases indispensable. The time is fast approaching, and in America may be said to have already arrived, when no further addition to the vast network of overhead telegraph and telephone wires in our towns will be permitted, and it is quite certain that no exception in favour of wires containing, so to speak, a large store of potential energy, will be made. Electric Light and Power Companies have realized this state of affairs from the beginning, and where they have come forward with definite proposals for a general supply, they have always arranged for their distributing plant to be placed underground. The case is different when electric transmission over a long distance, and possibly across country, is involved. Here the danger from breakage of an overhead wire can be almost entirely avoided by placing the supports at frequent intervals—a precaution not always possible in towns where the width of streets and places often necessitates an ex-

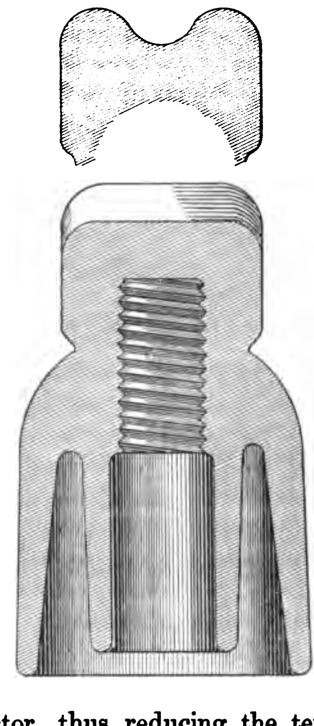
cessively long span from one support to the other—and if a wire should break, the chances of anybody being hurt are infinitely smaller than in the crowded streets of a town. We have already seen that power can only be economically transmitted over a long distance by the employment of a high electro-motive force, and hence the proper insulation of the line becomes a matter of the utmost importance. If, in a town district supplied with current at, say, 100 volts, a small leak of a few amperes should take place—and Mr. Edison's experience in the New York Central Station seems to show that such leaks do occasionally occur—the loss of energy, as compared to the thousands of amperes sent out from the station, is very trifling, but if an equal leak should be developed in a circuit of two or three thousand volts, it might very easily absorb all the current which the generating dynamo can pour into the cables, and no energy at all could be obtained from the motor. In an overhead line faults of insulation are not so easily developed, and if they occur, are more easily discovered and repaired than in any of the underground systems, which as yet have hardly had any prolonged trial to show their practical value; and for this reason it will be safe to assume that aërial conductors will be almost generally used for the *transmission* of electric energy at high potential over long distances, and that underground conductors will generally be used for the *distribution* of electric energy at low potentials.

Aërial Lines.

The conductor is generally a naked wire or cable of copper, iron, phosphor bronze, or silicon bronze, but slightly insulated conductors are sometimes used. The

insulation gives some protection against short circuits, which might otherwise be caused by other wires, branches of trees, or other bodies falling across the leads, and it has also the advantage of increasing the cooling surface

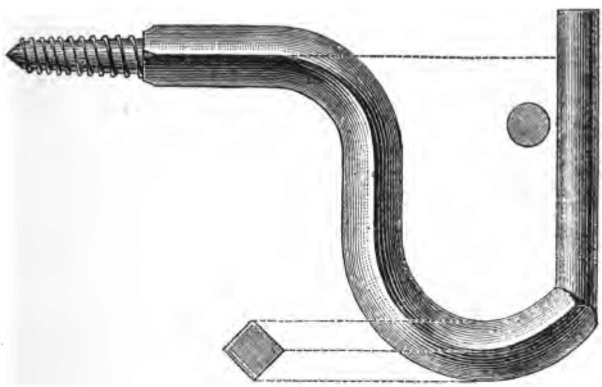
Fig. 68.



of the conductor, thus reducing the temperature. At first sight it might seem surprising that a wire coated with insulating material, which is necessarily also a bad conductor of heat, should become less heated than a naked wire. But such is the fact ascertained by experiments, and explained on the ground that quiescent air is the

very worst possible conductor of heat, whereas the material of the insulation, although relatively to metal a bad conductor, is a good one relatively to air. If the wire be exposed to wind, then air, although a bad conductor, carries heat off very fast, because each molecule of air as it becomes heated by contact with the wire is carried away and replaced by a new and cool molecule,

Fig. 69.

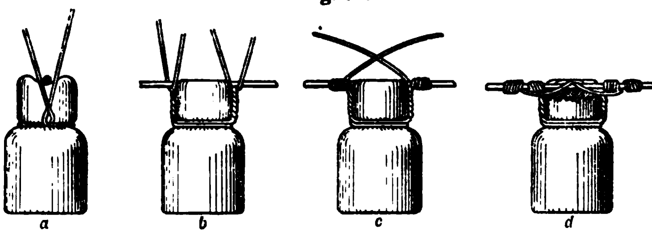


and in this case the insulated wire has no advantage over the naked wire.

The conductor is supported on porcelain insulators in the manner of telegraph lines, but to obtain a high degree of insulation they should be of the double-bell type, as shown in Fig. 68. The material should, when fractured, show a uniformly fine and dense grain free from pores and holes; it must be perfectly white, and contain no cracks or other flaws. The glaze must be perfectly white, and cover the whole external and internal surface with exception of the bottom rim of the outer bell. The thread must be even and well defined, without having broken parts. The stem, Fig. 69, is cylindrical

and roughened up. It is taped with yarn, served with linseed oil, and then screwed into the thread. To test the insulator electrically it is placed upside down, the inner space is filled with acidulated water, and it is then

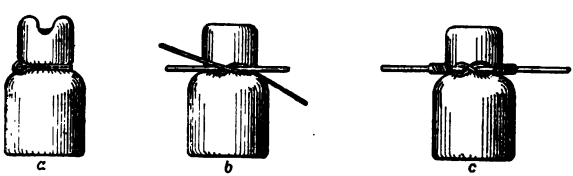
Fig. 70.



immersed to near the rim in a bath of acidulated water. If the insulation is perfect, it must be impossible to pass a current from the liquid on the inside through the insulator to the liquid on the outside.

The wire may be attached to the insulator either on the groove at the top or at the side, the latter if there

Fig. 71.



should be a bend in the line occasioning a considerable lateral strain. The method of attachment in both cases will be seen from Figs. 70 and 71, where the views *a, b, c, d* and *a, b, c* represent respectively the different stages of the process.

Since wire and cables can only be obtained and carried

to the place of erection in limited lengths, it is frequently necessary to make joints. A joint should not only be as strong as the wire or cable itself, but it must have an absolutely perfect contact, as otherwise the passage of the current would heat and ultimately destroy it. It is

Fig. 72.

also desirable to avoid the use of other metals than that of the conductor, so as to prevent electrolytic action. The use of solder is, of course, a necessity, and must be exempt from this rule; but it is not advisable to use

Fig. 73.

iron couplings for a line of copper, or any other combination of two different metals. With thin wires a strong joint is made, as shown in Fig. 72, which explains itself. To improve the contact, the middle portion is soldered

Fig. 74.

over. Fig. 73 shows another form of joint suitable for thin wires, which can easily be bent. A_1 A is one wire, B_1 B the other; the ends A and B_1 are left long enough to allow of being lapped round the middle portion of the joint until they meet, and are then twisted together, as shown in Fig. 74.

If the wire is too thick to allow of its being easily

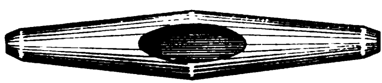
twisted into a knot, the joint shown in Fig. 75 is sometimes used. The two ends of the wire are bent short at right angles, and placed side by side, so that the ends point outwards. In this position they are held by a clamp whilst being served with a layer of binding wire

Fig. 75.

of the same material as the conductor. When the space between the two ends is completely filled by the binding wire it is soldered over.

Cables may be joined either by careful splicing or by couplings. A very neat coupling has lately been intro-

Fig. 76.



duced by Mr. Lazare Weiller; it consists of a double hollow cone (Fig. 76) with an opening in the middle. The end of the cable is inserted at one end, brought out at the central opening, then doubled over and pushed back again through the opening. A pull is applied to the cable as

Fig. 77.

if to draw it out of the coupling, and this has the effect of jamming the end of the cable tightly in the cone. The end of the second cable is treated in the same manner, and to secure perfect contact, and prevent any slipping back, melted solder is poured into the central opening. Fig. 77 shows the coupling in section and the cables in

place. As a suitable composition for the solder, Lazare Weiller recommends two parts of block tin to one part of lead. The wire cable and the coupling are both made of silicon bronze, and thus electrolytic action is avoided.

Material for Aërial Lines.

There are two requirements with regard to the material suitable for aërial lines which are to a certain extent contradictory. The specific resistance of the material should be very low, and its tensile strength very high. Now copper has of all metals which can practically be used the lowest resistance, but its breaking strain is comparatively low, and, therefore, the supports must be placed at frequent intervals and a considerable sag must be allowed in order to prevent the wire from being overstrained. The first circumstance increases the cost of installation, and the latter is objectionable because the probability of the wire coming accidentally into contact with neighbouring objects when swayed by the wind is increased. Iron, and especially steel, offers in this respect an advantage, but it has the drawback of being but a poor conductor of electricity. The conductivity of wrought iron is only about 17 per cent. of that of pure copper, and the conductivity of cast steel is only 10 per cent. of that of pure copper. If cast steel wire be used for the line, the total weight which must be supported by the insulators will, therefore, be between nine and ten times as great as that of copper wire of equal conductivity, and although the supports may be farther apart, each individual support must be much stronger than would suffice for copper wire. Thus there is no saving to be obtained by the use of the stronger material. As a

way out of this difficulty it has been proposed to use steel wire coated with electrolytically deposited copper. It was thus hoped to obtain a conductor which would combine the tensile strength of steel with the high conductivity of pure copper. This expectation was, however, not realized, and the compound wire has never come largely into use. The reason is not far to seek. Roughly speaking, the best steel has about three times the tensile strength of copper, and pure copper has about nine times the conductivity of steel. Imagine now a wire composed of equal parts of copper and steel, its tensile strength, even assuming that the electrolytically deposited copper takes its fair share of the strain, will be one-half plus one-sixth, that is 66 per cent. of that of a steel wire of equal diameter, the weight being about 5 per cent. greater on account of the greater specific weight of copper. The conductivity of the wire will be twice that of a steel wire of equal diameter, or 66 per cent. that of a copper wire of equal diameter. We have, therefore, the following relation:—

Pure copper wire, breaking strain 35,900 lbs. per square inch, conductivity	100
Steel wire, breaking strain 119,000 lbs. per square inch, conductivity	10
Compound wire, breaking strain 78,000 lbs. per square inch, conductivity	66

If we express the merit of a wire by the product of its breaking strain and conductivity, we find that the compound wire is only 30 per cent. better than the copper wire, and in practice this apparent gain will be, to a great extent, counterbalanced by the increased cost of

manufacture. Since the invention of the compound wire great strides have been made in the production of certain alloys which combine great tensile strength with a fairly good conductivity. The first in the series was phosphor bronze, having a breaking strain of 102,000 lbs. per square inch, and a conductivity of 26 per cent. Lately, Mr. Lazare Weiller introduced his silicon bronze, the conductivity of which is 97 per cent. of that of pure copper, and the breaking strain of which is half that of the best steel. For purposes of transmission of energy and for electric lighting he also makes silicon copper wires, for which he claims a conductivity lying between that of pure copper and that of silver; the breaking strain, however, is not given.[1] The following Table, taken from Herr Grief's book, but reduced to English measure, gives weight and resistance of this wire:—

[1] J. B. Grief, "Silicium-Bronze-Leitungen." Wien, Seidel und Sohn.

Silicon Copper Wire.

Diameter in Millimeter.	Diameter in English Mils.	Weight per Mile. lbs.	Resistance per Mile. ohms.
0·30	1·2	2·2	365·00
0·40	1·6	3·9	205·00
0·50	2·0	6·2	131·00
0·60	2·4	9·0	91·20
0·70	2·8	12·2	67·00
0·80	3·1	15·8	51·20
0·90	3·5	20·0	40·50
1·00	3·9	24·7	32.80
1·20	4·7	35·6	22·70
1·25	4·9	38·6	21·00
1·50	5·9	55·6	14·60
1·75	6·9	76·0	10·72
2·00	7·9	99·0	8·20
2·25	8·9	125·0	6·50
2·50	9·9	155·0	5·25
2·75	10.8	187·0	4·34
3·00	11·8	223·0	3·65
3·25	12·8	260·0	3·12
3·50	13·8	303·0	2·68
3·75	14·8	347·0	2·35
4·00	15·8	396·0	2·04
4·25	16·8	446·0	1·82
4·50	17·8	500·0	1·62
4·75	18·8	556·0	1·45
5·00	19·7	620·0	1·31

The following Table gives the relation between breaking strains in lbs. per square inch and conductivity for different materials :—

Material of Conductor.	Breaking strain.	Conductivity.
Pure Copper	39,500	100
Phosphor Bronze . . .	101,000	26
Silicon Bronze, Mark A .	63,200	97
" " Mark B .	79,500	80
Swedish Hammered Iron .	50,700	16·5
Swedish Bessemer Steel .	56,200	16·0
Siemens-Martin Steel . .	59,000	13·3
Cast Steel	133,000	10·5

The choice of material for an overhead line must depend on many local circumstances. As a general rule copper is preferable to iron or steel, and phosphor bronze, or silicon bronze, is preferable to pure copper. To show the saving in capital outlay which can be effected by the use of the latter material in comparison to iron, Herr Grief, in the book above mentioned, gives comparative estimates for a telegraph line of 1,000 kilometers (625 miles) in length. Although the line is longer than any which will probably ever be used for electric transmission of energy, and the wire is smaller than would generally be required for this purpose, these estimates have still some practical value as affording a ready means of comparing the two materials, and for this reason they are here added. The reader can see from these Tables how estimates for overhead lines are made up and what proportion the different items bear to the total cost. It will be noticed that the cost of the wire itself is not so great an item in the total cost as to greatly influence it. Although the silicon bronze wire costs nearly twice as much as an equivalent iron wire, there is yet a saving in the total capital outlay effected by its use. There are lighter supports and a lesser number of them required; the cost

of carriage and labour is reduced, and the subsequent cost of maintenance is also less.

Estimate I.—Galvanized Iron Wire, 5 millimeter diameter.

	Shillings.
Wire 156,000 kilos., at 304/ per 1,000 kilos.	47,424
Carriage for wire, 16/ per ton	2,496
Insulators, 15,000, at 160/ per 100	24,000
Fixing insulators and attaching wire, at 8/ per kilometer	8,000
Poles, 25 per kilometer (5 single and 10 double), at 9·60/ each	240,000
Carriage for poles, 80/ per 100	20,000
Erecting poles, 160/ per 100'	40,000
Joining double poles, 1·60/ per pair	16,000
Total	397,920

Estimate II.—Silicon Bronze Wire, 2 millimeters in diameter.

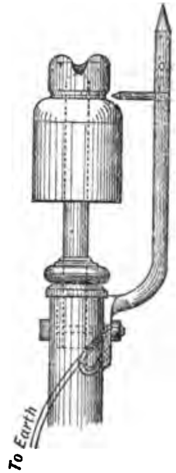
	Shillings.
Wire 28,000 kilos., at 3,200/ per 1,000 kilos.	89,600
Carriage for wire, 16/ per ton	448
Insulators, 12,000, at 80/ per 100	9,600
Fixing insulators and attaching wire at 3·2/ per kilometer	3,200
Poles, 16 per kilometer (8 single and 4 double), at 8/ each	128,000
Carriage for poles, 80/ per 100	12,800
Erecting poles, 160/ per 100	25,600
Joining double poles, 1·60/ per pair	6,400
Total	275,648

It will be seen that the total saving in favour of the more expensive silicon bronze wire is very considerable. It should also be remembered that this wire is hardly at all affected by the atmosphere, and that it retains nearly its full market value after the equivalent iron wire has been rendered valueless by rust.

Protection from Lightning.

Overhead lines, whether used for electric lighting or

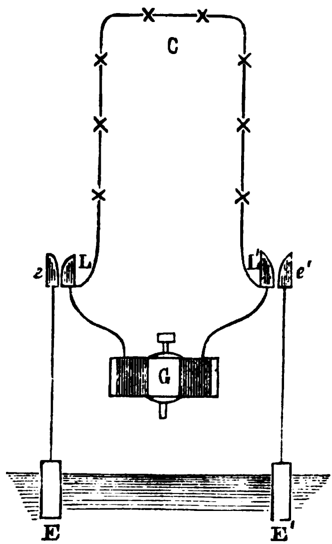
Fig. 78.



transmission of energy, are exposed to the effects of lightning, which may not only destroy the line, but also the dynamos or motors at either end. To protect the plant, various methods are in use, all of which are more or less modifications of the lightning protectors used in telegraphy, and which are based on the principle that a lightning discharge can leap a small break in a circuit to earth, which to the working current is impassable. Fig. 78

shows a lightning protector for the line. The vertical point acts as an ordinary lightning protector, so as to minimize the risk of the line being struck. Should this nevertheless happen at some place between two protectors, then the current will travel along the wire, and leap across to the horizontal point, and thus be conducted to

Fig. 79.



earth before it can reach the machinery at either end of the line. Another arrangement intended for the same purpose is that invented by Professor Thomson in connection with his system of arc lighting over long distances. It is, of course, equally applicable to long lines used for the transmission of energy. This protector, Fig. 79, permits a discharge to earth from both the positive and negative line, and it moreover automatically

ruptures any short circuit of the lines which may be thus started by the lightning current. It must be remembered that the electro-motive force employed in the Thomson-Houston system is very high (up to 2,000 volts), and that if an arc is formed between the metal parts of the protector, this electro-motive force would be high enough to sustain it after the lightning stroke has passed, and thus not only damage the protector, but possibly also burn up the dynamo. To prevent this a device is employed which automatically ruptures the arc. In Fig. 79 [1] G is the dynamo working the line, C; L and L^1, are plates of metal in connection with the line, and e and e^1 are similar plates in connection with earth at E, E^1. There is a small interval between e and L, and between e^1 and L, which, when a lightning discharge falls on the line, is easily leaped by it. The stroke is thus carried to earth. To rupture the arc formed, a magnet, M, Fig. 80, is employed. The plates L and E approach closely only at their lowest parts, and above are spread out as shown. The effect of the magnet, whose poles are flattened out as shown, is to repel upward the arc that may be formed between the plates L and E. The arc at once rises to the wider space and is thus broken.

Underground Lines.

A large number of systems of underground cables have been either proposed or tried, but as yet it cannot be said that anything like finality has been reached. The mains have been, and are still the most serious difficulty of electrical distribution. Edison was one of the first to

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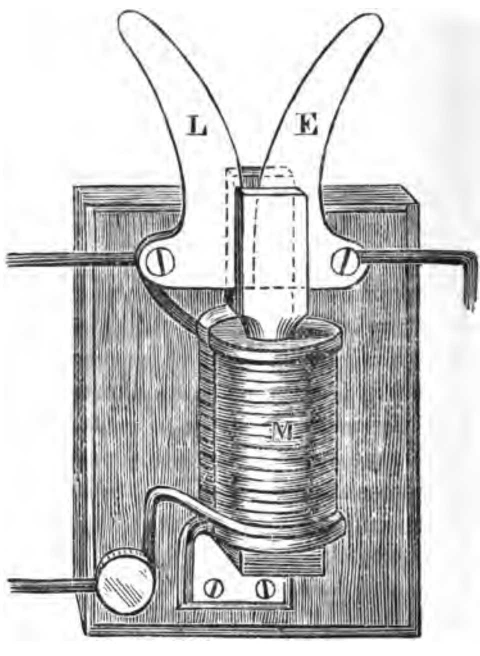
[1] The Author is indebted to the Editor of "The Electrical Review" for the use of this illustration and of Fig. 80.

grapple with the problem, and may be said to have found a solution which, if not perfect, at least has the merit of working. He originated the system of placing two half-round conductors into an iron pipe, the space between the conductors, and between them and the pipe being

Fig. 80.



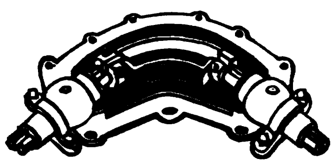
filled by a bituminous compound, which was poured in when liquefied by heat. The main was made in 20-feet lengths, the copper strips protruding at each end fo convenience of jointing. The joints were made by solder ing, which proved a very troublesome operation, becaus the thick copper strips carried the heat away almost a

fast as it was applied to the joint. To minimize this trouble it would have been advantageous to employ longer tubes, but that was found impossible, as the streets of New York, like those of any large town, are so cut up by gas, water, and drain-pipes, that no straight line of any length can be obtained. A short coupling-tube was placed over each joint connecting the iron pipes. Very soon after the installation was started troubles arose. The unequal nature of the ground, and the strains arising from the heavy traffic on the streets caused the pipes to be bent or broken, the conductors were thereby strained and worked through the bituminous compound until they came in contact and formed a short circuit, and the pipes were often accidentally damaged by the tools of workmen engaged upon some gas, water, or sewer work. The light wrought-iron piping at first employed was by degrees exchanged for strong steam-piping which could not easily be broken through by a pickaxe, and greater flexibility was given to the whole system by replacing the rigid couplings by ball-and-socket joints which permitted the mains to follow more or less any subsidence in the ground which might take place. The copper strips before being inserted in the pipe, were each taped singly, then served spirally with cord, laid together with their flat sides, and again wound spirally with cord. This prevented their coming in contact with each other, or with the sides of the pipe, even if the insulating compound should give way. Where a bend in the main is necessary, cast-iron elbows, as shown in Fig. 81, are introduced.

It is impossible to speak of underground conductors without making a digression to explain the so-called "three-wire system." It has already been pointed out that electric distribution, to be perfect, must insure the

independence of one motor from the other, and this can best be done by keeping the pressure in the mains constant, however the demand for current may shift and vary in different parts of the system, and at different times. Now, if we have a single pair of cables, one of them connected to the positive and the other to the negative terminal of the generator, it will be clear that on account of the resistance of these cables the current can only arrive at the motor after having undergone some loss of pressure, and this loss will be the greater the greater the current, or in other words, the more motors are at work on the same main at the same time. As far as motors

Fig. 81.



only are concerned the slight difference in electro-motive force thus occasioned would not be of any serious consequence, but as electric lamps must usually be fed from the same mains, it becomes very important to keep the pressure as nearly constant as possible. This can be attained by using a conductor of large size in comparison with the maximum current it has to carry. But we have already seen that the area of the conductor is determined by economical considerations, and any undue increase of the weight of copper laid down in the mains would render their cost prohibitive. The absolute variation in the pressure, both as regards distance from the generator and time, is thus a fixed quantity, and all we can do is to lessen the relative importance of this variation by working

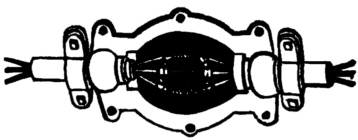
at as high a pressure as possible. A variation of five volts up and down of a standard pressure of, say, fifty volts, is a very serious matter, involving a difference of 20 per cent. between the highest and lowest pressure ; but if we can increase the standard to 200 volts the difference will be decreased to but 5 per cent., an amount which in practice will be found tolerable. Now, glow lamps as usually made require about 100 volts, and if our electric mains are to serve both for light and power purposes we must keep a pressure of 100 volts between them. If reliable lamps of 200 volts could be obtained we would be able to reduce the weight of mains to one-fourth of what is necessary at 100 volts, but since such lamps are as yet not to be had, we must look for some expedient which will allow us to use 100 volt lamps and at the same time work our supply at 200 volts. This is done by the three-wire system patented by Dr. J. Hopkinson in 1882. In this system two dynamos are used coupled in the following way. The negative terminal of the first dynamo to the negative main ; the positive terminal of the first dynamo to the negative terminal of the second dynamo and to a main called the balancing wire ; the positive terminal of the second dynamo to the positive main. The lamps and motors are attached in as nearly as possible equal proportion across the negative main and the balancing wire, and across the balancing wire and the positive main. If all are at work no current will pass along the balancing wire to the dynamos, but if some of the motors or lamps on either one or the other side of the balancing wire be switched off, then a differential current will pass along that wire to or from the dynamo whose circuit happens for the time being to do the greater part of the work. Since it is extremely unlikely that all the lamps or motors

to one side of the balancing wire will be switched off at the same time, this wire can be considerably smaller than any of the mains ; probably half the area will, in practice, be found sufficient. In this case the amount of copper required for the three-wire system working at 200 volts, as compared with the two-wire system working at 100 volts, is as follows : Each main carrying only half the current need only be half the weight. The balancing wire, carrying at most one-quarter the current, need only be one-quarter the weight. Therefore the total weight of copper will be $\frac{1}{2}+\frac{1}{2}+\frac{1}{4}$ in the three-wire system, and $1+1$ in the two-wire system, or the former saves 37 per cent. as compared to the latter. Mr. Edison has proposed to still further reduce the size of the balancing wire by providing each consumer with a switch which can be set to either one or the other main, the theory being that consumers will naturally set their switches so as to get the higher pressure, if there should be a difference due to unequal distribution, and thus mutually assist each other in getting the standard pressure, and relieve the balancing wire from having to carry any considerable current to or from the dynamos. As a further improvement, Professor Forbes has constructed an electro-magnetic apparatus which will automatically set the switch to one or the other main as soon as a certain difference in pressure should be exceeded. The three conductors—viz., the two mains and the balancing wire—are laid in one wrought-iron tube. Each conductor is wrapped with a layer of insulating tape and then wound spirally with a rope impregnated with some insulating compound liquefied by heat. The pitch of the spiral is large as compared with the diameter of the rope, so that the windings of the several conductors fit between each other when the con-

ductors are placed together. The three conductors are also bound together by a final spiral winding of rope around them all and then inserted into the tube. Molten insulating compound is poured into the tube at high temperature, ready access being afforded the liquid throughout the length of the tube along the spiral paths formed by the rope winding.

The joints between successive lengths of these "electric tubes" are made by means of special coupling-boxes with ball-and-socket connection shown in Fig. 82. Instead of soldering the ends of the conductors immediately together, short flexible couplings are employed, consisting of

Fig. 82.

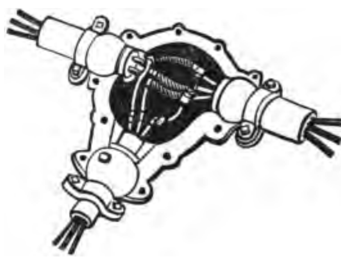


a piece of cable having cast or brazed on its end suitably shaped composition sockets, in which are drilled holes to fit the size of copper conductor, and to which they are soldered in laying the line. Three such cables are required for an ordinary joint. A modified coupling box is used for the connection of branch circuits to the main circuits. The construction of this will be clear from the illustration, Fig. 83, and after what has been said about the ordinary coupling box need not further be explained.

Another kind of junction, being essential to the system, must be here mentioned. It is the so-called "junction safety catch box," designed for connecting so-called "feeders" with certain points in the network of mains. By employing feeders the same result is obtained as if

the generator, which may be quite outside the district supplied, were actually placed at the feeding centre; and if we employ a sufficient number of feeders, each connected to its own dynamo, the pressure at the terminals of which can be varied so as to keep the pressure at each feeding centre constant, we have virtually transferred each dynamo to its feeding centre, that is, into close proximity of the points of consumption. The equalization of pressure throughout the district supplied is thereby

Fig. 83.



much facilitated. At the Edison installation in New York there are twenty separate feeders. The junction safety catch box is a large round box, the top of which is flush with the surface of the street. It has a loose outside cover and an inside cover which is bolted on to make a water-tight joint with the box. The central part of the box is occupied by three pole pieces corresponding to, and connected with, the three conductors in the feeder, these pole pieces being gun-metal rings, each having as many radial projections as there are mains connected with the box. The pole pieces, as well as all the other electrical fittings within the box to be presently described, are insulated from each other and from the box. The radial projections terminate in plane, polished, gold-plated sur-

faces, one inch square, which are arranged symmetrically around the centre of the box and equi-distant from it. The terminals of the mains are arranged in three other circles, each respectively on the same level as the corresponding polar ring, but of larger diameter, and the safety fuses, also provided with gold-plated terminals, connect each pole piece with the terminal of the main radially opposite to it. The electric tubes containing the mains enter the box two feet below the surface of the street, and the connection between them and the box is made water-tight. If from any reason—a short circuit or a heavy leak—the current through any of the mains becomes too strong, the safety fuse connecting that main with the feeder melts and interrupts the current until the damage has been repaired and a new fuse inserted.

Another system which has already passed the first experimental stages is that of the *American Sectional Underground Company.* It is intended for the accommodation of telephone, telegraph, electric light, and electric power wires, all in the same duct, but separated from each other by shelves. The largest size duct yet made is a cast-iron pipe of rectangular section, ten inches by fifteen inches, costing £3,000 per mile when laid. The pipe is provided at every street-corner with a man-hole large enough for one or more men to enter for the purpose of hauling in the wires and making the necessary connections. There are further, at convenient distances along the line of conduit, hand-holes for tapping the wires for house-to-house supply. The connection with the house wires and mains are made at the nearest man-hole, and the house-wires are run along an upper shelf in the duct devoted for that purpose until the hand-hole is reached, where they are taken out and across to the house. It is

claimed as a special feature of this system, that through the interposition of shelves the telephone wires are guarded from induction from the electric light and power wires. On the other hand, it seems doubtful whether the insulation of heavy cables, after they have been dragged along the shelves, will remain perfect. To provide against water the man-holes are provided with sumps connected to the street drains, and open gratings are placed at certain man-holes, by which means sweating and condensation in the duct itself are prevented.

The Brooks Underground Conduit.—The conductors are laid in wrought-iron pipes with suitable splice-boxes, hand-holes, and outlets. To protect the pipes from oxidation they are laid in a wooden trough, into which hot pitch is poured so as to completely envelop the pipes. The conductors are made up into bundles, soaked in hot mineral oil, and drawn into the pipes in 2,000 feet lengths. A heavy mineral oil is then forced into the conduit for the purpose of excluding moisture and increasing the insulation. To show the efficacy of this oil as a means of insulation, Mr. Brooks, at the Philadelphia Exhibition, showed the following experiment. Two wires were attached to a Holz induction machine, and their extremities dipped into the oil. They were so placed as to be $\frac{1}{4}$ inch apart in the oil and $1\frac{1}{2}$ inch apart at the surface. On turning the machine the spark passed through the $1\frac{1}{2}''$ of air-space at the surface, but not through the oil, although there the leaping distance was much smaller.

In all the systems above described the leading idea is to provide for the conductor, in the first instance, an insulation so perfect and of such thickness that moisture cannot get to the metal of the conductor, and so cause leakage.

The Continental Underground Cable Company prefer to use for their conductor a cheap and thin insulation, but they endeavour to surround it with an atmosphere of perfectly dry air under pressure. This is done by building conduits with walls of asphalte blocks or other anti-moisture material, and providing them with iron supports and semicircular wrought-iron troughs for the accommodation of these lightly insulated mains. The mains are hauled through from one man-hole to the other by means of a cord, which has, in the first instance, been sent through the conduit by a carriage propelled by an electric motor. Very light wires can be laid direct by this carriage. It is proposed to close, as hermetically as possible, the whole of the conduit, and to force air into it which has been deprived of all moisture by being passed over some chemicals. Safety-valves are fitted at the end of the conduit where this air may escape if the pressure rises beyond a safe limit. As far as the author is aware this system has not yet been practically applied.

Lead-Covered Cables.—Perhaps the most simple, and certainly a very efficient way of keeping cables dry, is that of surrounding each cable with a continuous sheath of lead. The cable, after having received the usual insulation, is passed through a machine which, by hydraulic pressure, surrounds it with a cylindrical coating of lead free from any open joints, flaws, or other imperfections through which moisture might enter. The cable, thus protected, can be laid either directly into the ground or into a trough made of brickwork filled with loose sand, and then covered over by flags or brickwork. M. Marcel Deprez has used forty-five miles of lead-covered cable in his Paris-Creil experiments on the electric transmission

of energy.[1] If special protection is required a second lead sheathing is put over the first. The following Table gives the weight of single and double lead-covered cable of different cross-sectional area.

Section in square inches.	Weight in pounds per mile.		Ohms per mile.
	Single Covering.	Double Covering.	
·007088	1,150	1,714	6·36
·009331	1,234	1,819	4·84
·011083	1,430	2,092	4·05
·011309	1,489	2,209	3·99
·013193	1,516	2,235	3·40
·014102	1,663	2,400	3·19
·015280	1,795	2,613	2·94
·016960	1,817	2,653	2·65

[1] This was, however, a mistake, because with the high pressure employed the lead covering of the cable acted as an enormous condenser and gave rise to heavy electro-static induction. It seems that lead-covered cables would be only applicable for currents of low electro-motive power.

CHAPTER IX.

Possible Applications of Electric Transmission of Energy—Best Field for it is Long Distance Transmission—Comparison with other Systems—Herr Beringer's Investigation—Hydraulic Transmission—Pneumatic Transmission—Wire-Rope Transmission—Comparative Tables of Efficiency and Cost—Practical Conclusions.

IF we would judge fairly the merits of a new invention, we should not only look upon it by itself, but compare it with all that has gone before and might be superseded by it. This is especially the case if we have to deal with a new thing that has many rivals, and the electric transmission of energy is precisely in this position. Ever since man began to use tools worked by other than manual power, he had to employ some system of transmission of energy, and as a natural consequence the number of systems is not only very large, but each has in the course of time been brought to great perfection. Electric transmission has therefore to compete with a host of mechanical devices, and it becomes important to compare it with them. Some enthusiasts predict that in the near future all belts, pulleys, shafts, ropes, and cog-wheels will be superseded by electric wires and motors. Thus Mr. Walker, in "The Electrician" of Jan. 8, 1886, says: "How easily and how quickly, and with little occasion for repairs, can two cables be laid, in almost any position, for mines, ironworks, docks, factories, as compared with shafting, ropes, steam-pipes, compressed air. I have

every confidence that the day will come when shafting and belts in factories will be looked upon as a barbarism, and people will wonder however they endured it so long." As a matter of fact, there are already several engineering works where electric transmission of power is largely used. Messrs. Ducommun in Mulhouse, the Foundry of Cannon in Ruelle, the École Industrielle in Saint-Chamond, the ironworks in La Buire, the workshop of Sir David Salomons, and a private workshop of Sir W. Armstrong, in all these instances electro-motors are used. In the works of the Société Gramme, and in those of the Compagnie Électrique, there is not a single shaft worked by belt, all the tools being coupled direct to small electro-motors which are supplied with current from one generator driven by the main engine. It is estimated that the total efficiency of the installation reaches but fifty per cent.—that is, only half the power of the engine is actually obtained at the tools. This might seem a poor return, but on the other hand there is no necessity for heavy walls, columns, or other supports to carry overhead shafting, no attendance is required for keeping the bearings in proper order, and, above all, there is no intricate mass of belting, the maintenance of which is expensive, and which often presents a source of danger. Moreover, it is claimed that transmission by shafts and belting has generally a lower efficiency than fifty per cent., because of the great weight of machinery which must at all times be kept in motion, irrespective of the number of tools at work at any moment, and irrespective of the load on each tool. With electric transmission, on the other hand, no power is consumed, and none is transmitted for those tools which are idle, and the power transmitted to the tools at work is always proportional to the amount of work they are

doing. It is this peculiarity of electric transmission, that the power consumed is always proportional to the work performed, which renders it on the whole more economical than some other and purely mechanical devices.

Whether electricity is ultimately destined to supersede shafting pulleys and other gear now commonly used for transmission of energy over short distances is a question which only enthusiasts, or those imperfectly acquainted with the technical part of the subject, can be bold enough to answer. The practical engineer is content to go step by step, and to solve those problems which appear most promising before he attacks those less certain of success, and viewed in this light it would seem that long distance transmission offers a better field for the application of electricity than short distance transmission. The reason is not that it is easier to transmit energy electrically over longer distances, but that the difficulties of employing purely mechanical means are so great as to make competition easier. The difficulties of all systems of transmission increase with the distance, but for electricity not so much as for mechanical means, and consequently the advantages of electric transmission become more apparent at long distances.

There are four systems of importance suitable for long distance transmission:—

The electric transmission of energy.

The hydraulic transmission of energy.

The pneumatic transmission of energy.

The transmission of energy by wire rope.

We do not mention steam as a means for transmitting energy over long distances, because it has not come into extensive use. It is, moreover, unnecessary to consider this system specially, as the investigation of pneumatic

transmission would with certain small modifications be also applicable for steam instead of air. We also exclude from our list the transmission of energy by means of coal gas, taking place daily between the distant gas-works and numerous gas-engines working from the mains in the centre of the town. In this case we transmit, strictly speaking, energy, but it is energy in a latent form, and not potential energy, as in the systems above mentioned. We also leave out of consideration the idea to transmit energy by means of a revolving shaft extending over the whole distance, as something quite impracticable. Even if the cost of such a plant, and the difficulty of providing suitable bearings would not be the formidable obstacles they are, the system would yet be quite unsuitable for long distances, because the friction of the long shaft in its journals would absorb too much power. A simple calculation shows that with bearings perfectly in line, and good lubrication, a wrought-iron shaft of uniform thickness and two miles in length, cannot be turned from one end because the resistance of friction is greater than the torsional moment which can safely be applied. If the shaft be one mile in length, fifty-five per cent. of the power which can safely be applied, is required to overcome its own friction, leaving only forty-five per cent. to be recovered at the distant end, whereas in a shaft 100 feet in length only one per cent. is wasted in friction. These figures show that transmission of energy by shafting is only economical when applied to short distances, and for our present purpose it need therefore not be further considered.

Returning now to the four systems which can be fairly considered to be competitors for long distance transmission, the choice of one or the other of them must to a

great extent depend upon local circumstances. If the latter are equally favourable to all the four systems, then the factors which will determine the choice are: The power to be transmitted, the number of hours per annum during which the plant is at work, the price of one-horse power hour at the generating station, and its commercial value at the receiving station, and finally the distance of transmission. Herr Beringer, in his interesting work [1] on this subject, has made the attempt to compare in a general way the electric transmission of energy with the other three systems above mentioned. In making the comparison it is, of course, necessary to start with certain assumptions which should, as nearly as possible, represent the average conditions of actual practice. Thus Herr Beringer assumes as a basis for his calculations two sources of energy, steam and water. As regards the former he adopts Grove's valuation of one horse-power hour, which costs in

Small steam-engine . . .	3·80 pence.
Medium size steam-engines .	2·63 ,,
Large steam-engines . .	1·02 ,,

If the engine is at work for 300 days per annum, and for ten hours during each day, the annual cost of one horse-power when using large engines would, therefore, be £12 14*s*. As regards water-power, Herr Beringer adopts Meissner's estimate, according to which water-power costs one-fifth to one-tenth of steam-power. Under the above conditions he fixes the price of one annual horse-power obtained by water at £2 16*s*. A similar calculation for gas-engines, assuming that they require

[1] Beringer, "Kritische Vergleichung der Elektrischen Kraftübertragung." Springer, Berlin, 1883.

30 cubic feet of gas per horse-power hour, and that gas costs 3*s*. 6*d*. per 1,000 cubic feet, brings the price of one horse-power hour up to 2·7 pence. This is inclusive of interest and depreciation and of attendance. Since both gas-engines and small steam-engines can be erected in almost any locality, it would obviously be useless to transmit the power of these prime movers to any distance. A system of transmission will only pay if the cost of the power received at the distant end is less than the price which would have to be paid for its production there, and consequently we need only take those cases into consideration where large steam-engines or water-wheels, producing power at a cheap rate, are employed at the generating station.

It has already been pointed out that the theoretical economy of electric transmission increases with the pressure employed. On the other hand, the difficulties of producing suitable machines, of maintaining the insulation of the line, and the risk entailed in a failure of insulation are all greater with a system where a very high pressure is used, and for these reasons it seems advisable to fix the pressure at a moderate limit. Herr Beringer assumes 1,500 volts as a limit sufficiently high to insure economical transmission, and yet not too high for safe working. He estimates the cost of electric transmission when 5, 10, 50, and 100 horse-power are required at the receiving-station, and in all cases for distances of 100, 500, 1,000, 5,000, 10,000, and 20,000 meters distance. The prices taken for dynamos and motors are rather higher than the present market prices, and thus his estimates are slightly less favourable than they need be. Thus a dynamo to give 8 electrical horse-power output is valued at £200, whereas such a machine of approved construction can now

be had in the open market for £130. The comparison between electric transmission and mechanical systems is, therefore, less advantageous to the former than it would be if present market prices had been taken for the basis of these estimates ; but the fault is one in the right direction, and shows that Herr Beringer was not biassed in favour of the electrical system. The conductor is, in all cases, supposed to be bare copper wire carried overhead on poles and insulators, and separate wires for the out-and-home circuits are used. The diameter of the wire is calculated on Sir W. Thomson's rule for greatest economy. In all twenty-four estimates were made, and the result is given in the following table, the figures in which represent the capital outlay in pounds sterling per horse-power obtained at the receiving station. The cost of the prime mover and that of buildings, boilers, chimney, hydraulic works are not included, as account is taken of these items in the estimate of the annual value of one horse-power as produced by the prime mover. The cost of foundations for dynamos and motors, that of measuring instruments and switches, are, however, taken into account:—

Maximum Horse-Power Transmitted.	Capital Outlay reduced to One Horse-Power transmitted over a distance of					
	100 m.	500 m.	1,000 m.	5,000 m.	10,000 m.	20,000 m.
5	75	78	81	108	142	210
10	52	54	56	77	103	154
50	40	41	42	55	69	100
100	32	33	35	45	59	87

In estimating the working expenses the author allows 14 per cent. of the capital outlay for interest and depre-

ciation, and he assumes that the commercial efficiency of electric transmission over the distances of

	100	500	1,000	5,000	10,000	20,000 meters
is	·69	·68	·66	·60	·51	·32.

For each horse-power obtained at the receiving station there must consequently be produced at the generating station—

1·45 1·47 1·51 1·67 1·96 3·12 horse-power.

Allowing 1·02 pence as the price to be paid per horse-power hour at the generating station, the prime mover being supposed to be a large steam engine, the cost of one horse-power hour at the receiving station is

1·48 1·50 1·54 1·70 2·00 3·18 pence,

which, added to the figures representing interest and depreciation, gives the following values for one horse-power hour obtained at the receiving station.

Energy obtained by large Steam Engine.

Maximum Horse-Power Transmitted.	Price of One Horse-Power Hour in Pence transmitted over a distance of					
	100 m.	500 m.	1,000 m.	5,000 m.	10,000 m.	20,000 m.
5	2·25	2·33	2·41	2·87	3·29	5·20
10	1·98	2·07	2·14	2·53	3·10	4·85
50	1·87	1·94	1·99	2·28	2·74	4·25
100	1·79	1·85	1·91	2·18	2·63	4·08

In compiling this table it has been assumed that the plant is at work for 3,000 hours per annum.

If water-power has to be transmitted, it will in most cases be advantageous to keep the plant at work night and day, because, in so doing, a maximum of horse-power hours is obtained from a given plant. Under these conditions the price of one horse-power hour in pence is as shown in the following table :—

Energy obtained by Water Motor.

Maximum Horse-Power Transmitted.	Price of One Horse-Power Hour in Pence transmitted over a distance of					
	100 m.	500 m.	1,000 m.	5,000 m.	10,000 m.	20,000 m.
5	·35	·36	·37	·44	·52	·84
10	·27	·28	·29	·36	·47	·71
50	·23	·24	·26	·29	·37	·55
100	·20	·22	·23	·26	·32	·50

The hydraulic transmission of energy presents many points of resemblance with the electric transmission. We have at the generating station a force pump which delivers water under high pressure into a pipe leading to the receiving station, where part of the energy is recovered by a water motor. To minimize the loss of energy due to the friction of the water against the pipe, the velocity of flow should be as small as possible, or, in other words, the diameter of the pipe should be as large as possible. In thus trying to increase the economy of the system, we incur a larger capital outlay ; and applying Sir William Thomson's rule also to this case, we find that there exists for every given set of conditions, one particular diameter of pipe for which the sum of the annual value of energy wasted, and the annual interest on capital outlay becomes a minimum. So far the analogy with the electrical

system is perfect. But there enters another element into the calculation which to a certain extent modifies the law. It has been shown that the most economical size of a copper wire depends only on the current, but not directly on the pressure. It depends on the pressure indirectly, inasmuch as with an increased pressure a given amount of energy can be transmitted by using a reduced current, and this again involves a reduction in the size of the conductor. But if the current be a fixed quantity, an increase of pressure does not entail a greater outlay for conducting material. It might very slightly increase the cost of the installation by necessitating a more careful insulation; but the difference in expenditure for a good and a perfect insulation is not a great item. With hydraulic transmission the case is different. An increase of pressure does entail a greater outlay for conducting material, because the thickness of metal in the pipe must be increased as the pressure is increased; therefore the cost of the conductor depends not only on the quantity of water to be transmitted, but also on the pressure. A natural limit is thus set to the increase of pressure by financial considerations which are absent in the case of electric transmission. The pressure is also limited by technical considerations. In the first place the water motor is an engine with bearings and other moving parts, which can only work satisfactorily, and without heating or undue wear, if the pressure between the moving surfaces in contact remains within reasonable limits; the same as in any other engine. In the second place, if the pressure be increased beyond a certain limit depending on the tensile strain of the material of the pipe or working cylinder, no increase in the thickness of metal can save these parts from bursting, as every engineer knows.

Such a limit to electric pressure does not exist in dynamo machines or electro-motors. It is perfectly conceivable to employ any desired pressure provided we increase the thickness of insulation sufficiently.

Another point where there is a vital difference between electric and hydraulic transmission of energy is that the electro-motor has nearly the same commercial efficiency, whether fully loaded or not, whereas the water-motor when working light has a very much smaller efficiency than when fully loaded. Hydraulic transmission can, therefore, only be employed where the question of efficiency is of secondary importance, or where the amount of energy to be transmitted is not subject to variations.

All the above remarks, save the last, apply also to *pneumatic transmission.* But since the friction of compressed air against the walls of the pipe is less than that of water, the pneumatic system can be used over greater distances than the hydraulic system. It is also possible to obtain a higher efficiency with varying loads by providing the receiving machine with a variable expansion gear. There is, however, another drawback peculiar to the employment of an elastic fluid. It is well known that heat is generated in compressing air. To prevent the air-pump from becoming too hot, the air in the act of being compressed must at the same time be cooled, which is done either by surrounding the compressing cylinder with a water-jacket, and also by circulating water through the interior of the compressing piston, or by injecting a spray of water at each stroke of the piston. The latter is by far the more effective plan, and has been adopted by M. Colladon in his air-compressors used in the works at the Gothard Tunnel. The air, which is always charged more or less with moisture (irrespective of the water in-

jected), upon expanding and performing work in the receiving engine, becomes reduced in temperature, and thus there is danger that snow will be deposited in the valves and passages of the engine. This danger will be the greater the more expansively the engine works—that is to say, the more economical we wish to render the system. To prevent the engine from becoming clogged by snow and ice, it is therefore necessary to apply heat in some form, and that is generally done by injecting hot water. It need hardly be pointed out that the complications thus introduced at the generating station and at the receiving station, and the increased working expenses entailed, are very objectionable features of pneumatic transmission, counterbalancing to a great extent the economical advantage it has as compared to hydraulic transmission.

The transmission of energy by wire rope invented in 1850 by M. Hirn is the most simple, and, up to reasonable distances, the most economical of all the known means of transmitting energy. The system is so generally known that a detailed description need not be given in this place. Suffice it to say that the principal sources of loss of energy are, 1. Friction in the bearings of the rope pulleys; 2. Air resistance; 3. Stiffness of ropes. The loss occasioned through the slipping of the rope on its pulleys is so small that it can be neglected. The pulleys are placed about 100 yards apart. Greater distances are sometimes used, but are avoided where possible, as the sag of the rope requires too much head room, the influence of temperature in contracting and expanding the rope becomes too great, and the handling of the rope for renewal or repairs becomes too difficult. From data obtained with wire-rope transmissions actually in-

stalled over distances varying between 100 and 1,000 meters, Herr Beringer calculated the efficiency of the system as follows:—

Distance	100	500	1,000	5,000	10,000	20,000 meters.
Efficiency	·96	·93	·90	·60	·37	·13

The rapid falling off in efficiency for the longer distances is due to the large number of intermediate stations necessary on account of the span being limited to 100 meters.

The author in the book above mentioned gives a large number of estimates for transmission by water, air, and wire rope, calculated in the same manner as for elec~~tive~~ric transmission. We need in this place not follow him into all the details, but must be content to note the final results of his calculations as being more directly of interest to our subject. The following comparative table shows the commercial efficiency of the four rival systems for different distances of transmission:—

Commercial Efficiency.

Distance of Transmission.	Electric.	Hydraulic.	Pneumatic.	Wire Rope.
100 m.	·69	·50	·55	·96
500 m.	·68	·50	·55	·93
1,000 m.	·66	·50	·55	·90
5,000 m.	·60	·40	·50	·60
10,000 m.	·51	·35	·50	·36
20,000 m.	·32	·20	·40	·13

It will be seen that for distances less than 5 kilometers (about three miles) transmission by wire rope is more economical than that by any other system. For distances

greater than 5 kilometers the electric transmission is most economical. As regards capital outlay, the wire-rope system is also for short distances more advantageous than electric transmission, the limit being at about 3 kilometers (a little under two miles). Beyond that the electrical system is the cheapest, as will be seen from the annexed table :—

Capital Outlay in Pounds Sterling reduced to one Horse-Power.

Maximum Horse-Power Transmitted.	System of Transmission.	Over a distance of					
		100 m.	500 m.	1,000 m.	5,000 m.	10,000 m.	20,000 m.
5	Electric	75	78	81	108	142	210
	Hydraulic	41	66	97	358	610	1280
	Pneumatic	73	96	210	600	1090	2060
	Wire Rope	6·5	31	61	305	760	1220
10	Electric	52	54	56	77	103	154
	Hydraulic	30	45	65	220	416	806
	Pneumatic	60	72	88	213	369	680
	Wire Rope	5·1	23	47	231	460	925
50	Electric	40	41	42	55	69	100
	Hydraulic	16	21	30	91	170	325
	Pneumatic	31	36	42	88	147	265
	Wire Rope	1·8	7·2	14	69	136	272
100	Electric	32	33	35	45	59	87
	Hydraulic	14	20	28	88	164	310
	Pneumatic	26	30	34	67	109	192
	Wire Rope	1·1	4·3	8·4	41	81	162

The table shows that for short distances the cost of electric transmission is very considerable as compared to that of the other systems. The reason for this is that the prices of dynamos and motors have been rather over-estimated, as already mentioned. For long distances this is not so noticeable, as the conductor forms the more important item, and especially since an electric wire is cheaper than an equivalent hydraulic or pneumatic tube.

If we compare the conductors only we find that for the transmission of 10 horse-power a copper wire of 127 mils diameter (*N°* $10\frac{1}{2}$ *B. W. G.*) is equivalent to a water-pipe of $3\frac{7}{8}''$ diameter, or to an air-pipe of $3\frac{1}{8}''$ diameter, or to a wire rope of $\frac{5}{16}''$ diameter. The proportion between the cost of these conductors calculated for equal distances is as

$$1{\cdot}4 : 34{\cdot}8 : 27{\cdot}8 : 1$$

The conductor with hydraulic transmission costs therefore twenty-five times as much, and with pneumatic transmission it costs nearly twenty times as much as with electric transmission. These figures prove that as far as capital outlay is concerned, the electric system has the greatest advantage where the conductor is long, that is, where the energy has to be transmitted over a long distance.

It would, however, not be correct to compare the four systems on this basis alone. The comparison must be made on the question of capital outlay combined with efficiency, in other words, the figure of merit for each system is the price which has to be paid for one horse-power hour at the receiving station.

Price in Pence of One Horse-Power Hour obtained at the Receiving Station.

Maximum Horse-power transmitted.	System of Transmission.	Steam Power Transmitted over a distance of						Water Power Transmitted over a distance of						Cost of Steam Power produced at Receiving Station.
		100 m.	500 m.	1,000 m.	5,000 m.	10,000 m.	20,000 m.	100 m.	500 m.	1,000 m.	5,000 m.	10,000 m.	20,000 m.	
5	Electric	2·25	2·33	2·41	2·87	3·29	5·20	·35	·36	·37	·44	·52	·84	3·80
	Hydraulic	2·50	2·84	3·15	6·52	10·50	19·00	·29	·38	·48	1·38	2·50	4·79	
	Pneumatic	2·70	2·96	3·30	5·25	9·53	16·72	·40	·47	·58	1·27	2·40	4·45	
	Wire Rope	1·13	1·45	1·88	5·45	10·40	22·70	·11	·19	·30	1·25	2·50	4·86	
10	Electric	1·98	2·07	2·14	2·53	3·10	4·85	·27	·28	·29	·36	·47	·71	2·63
	Hydraulic	2·38	2·55	2·79	5·08	7·70	14·30	·25	·30	·37	·95	1·54	3·17	
	Pneumatic	2·54	2·69	2·87	4·48	6·25	10·40	·35	·38	·44	·88	1·42	3·97	
	Wire Rope	1·12	1·38	1·70	4·50	8·50	19·10	·09	·17	·25	·96	1·91	4·00	
50	Electric	1·87	1·94	1·99	2·28	2·74	4·25	·23	·24	·26	·29	·31	·55	1·02
	Hydraulic	1·63	1·70	1·80	2·90	4·21	7·80	·15	·18	·22	·46	·76	1·43	
	Pneumatic	2·02	2·11	2·18	2·87	3·54	5·30	·22	·24	·28	·44	·65	1·08	
	Wire Rope	1·08	1·18	1·30	2·54	4·51	11·10	·09	·11	·13	·38	·72	1·61	
100	Electric	1·79	1·85	1·91	2·18	2·63	4·08	·20	·22	·23	·26	·32	·50	1·02
	Hydraulic	1·62	1·70	1·78	2·87	4·15	6·84	·16	·17	·19	·43	·72	1·14	
	Pneumatic	2·00	2·04	2·09	2·63	3·10	4·50	·22	·23	·24	·36	·48	1·33	
	Wire Rope	1·07	1·14	1·22	2·21	3·83	9·73	·08	·10	·11	·28	·48	1·19	

The smaller this price, the better the system. A glance at the annexed table will show that the cost of one horse-power hour increases in all systems with the distance, but with electric transmission the increase is not so rapid as with the other systems. The table also shows that up to a distance of 1,000 meters (five-eighths of a mile), wire-rope transmission is better than electric transmission, but above that limit the electrical system is better. Hydraulic and pneumatic transmission are in some few cases better than electric transmission, but then the wire rope is again better than either, so that there does not seem to be a field for the application of the hydraulic or pneumatic system, except in cases where the other two systems are for some local reason inadmissible, or where the water and air may be of further use after the power has been obtained from them. This, for instance, is the case with the pneumatic transmission employed in the building of tunnels. Here it is an absolute necessity to force air to the end of the workings for ventilating purposes, and pneumatic transmission is adopted in preference to any other system which would require some special ventilating plant being erected.

The last column on the right in the table gives the cost of one horse-power hour in pence, obtained from a steam-engine placed at the receiving station, in which case the transmission becomes unnecessary. It is evident that it will always pay to place a steam-engine if the power from it can be had at a cheaper rate than it can be brought from a distant source. If the source be water-power transmitted electrically, then the local engine is more expensive in all cases comprised within the limits of the table ; but if the source is a steam-engine then it depends on the distance and the amount of power re-

quired, whether a local steam-engine can produce the power more cheaply or not. Say we require ten horse-power at the receiving station. We can obtain this power at the expenditure of 2*s*. 2½*d*. per hour with a small steam-engine erected there. Now if a large steam-engine, working very economically could be found within a radius of say two miles from the place where we require ten horse-power, we might utilize this engine to drive a generating dynamo and transmit the energy electrically. The hourly cost of ten horse-power actually obtained from the electro-motor would then be about 2*s*., or ten per cent. less than the power obtained from a local engine. In this case it would barely pay to use electric transmission. If the distance were a little more than two miles it would certainly not pay. On the other hand, if the power required is small, say under five horse-power, then electric transmission shows a considerable advantage. Thus five horse-power produced in a small local steam-engine cost 1*s*. 7*d*. per hour, whereas we might transmit the same power over a distance of two miles at a cost of 1*s*. 1*d*., which represents a saving of 6*d*. per hour.

Summarising the results detailed in the table, we come to the following conclusions:—

1. It pays to transmit cheap water-power; by wire rope if the distance is less than a mile, and electrically if the distance is a mile or more. This applies to all powers.

2. It pays to transmit cheap steam-power if the amount of energy required at the receiving station does not exceed ten horse-power. If the distance is less than a mile use wire-rope transmission; for distances of one mile and upwards, up to two or three miles, use electric transmission. Beyond this limit a small local steam or gas engine is preferable.

CHAPTER X.

Classification of Dynamo Electric Machines—The Edison Dynamo—The Edison-Hopkinson Dynamo—The Thomson-Houston Dynamo—The Immish Motor—The Manchester Dynamo—The Elwell-Parker Dynamo—The Elwell-Parker Motor—The Crompton Dynamo—The Goolden Trotter Dynamo—The Andrews Dynamo—The Kapp Dynamo—The Phœnix Dynamo—The Reckenzaun Motor—The Victoria Dynamo—The Gülcher Dynamo.

IN the foregoing chapters we have dealt with the general principles of electric transmission of energy, and with the general conditions to be fulfilled by the generator and receiver, without, however, limiting the investigation to any special type of dynamo machinery. It will now be necessary to confront the subject from a more practical point of view by entering in detail into the types of dynamos and motors at present in use. In so doing the author must point out that the present book is not intended to teach how dynamo machinery should be designed and practically constructed. This is a subject so vast, that its treatment could well fill two such volumes as the present one, and will therefore not be attempted in these pages. The question is rather, how existing types of dynamos and motors can best be utilized for the electric transmission of energy, and for this purpose it suffices to give a descriptive account of those types of dynamo electric machines which have been found practically successful. Both as regards generator and receiver

the machines can be classified in the manner adopted in Chapter IV. according to the type of armature employed.

We distinguish three types of armature :—

I. The Drum, where the wire is wound along the surface and over the ends of the core.

II. The Cylinder, where the wire is wound along the surface and through the internal space of the core.

III. The Disc, which only differs from the cylinder by the proportions of the core, the diameter being large in comparison to the length.

It may be well to point out in this place that the drum requires less wire than the cylinder to produce the same electro-motive force, because the end connections in the former are generally shorter than the internal connections in the latter type ; but it has this practical defect, that at the ends the different wires cross each other in many layers. This is objectionable for two reasons. In the first place, wires between which a great difference of potential exists, are brought close together, whereby the liability to short circuits is increased, and in the second place repairs are very difficult, because in order to reach any particular wire, all those coils which are wound over it must first be removed. In the cylinder and disc armatures, on the other hand, neighbouring wires on the outside as well as on the inside are never at a great difference of potential, and each coil can be removed and replaced without disturbing the rest of the winding.

Each of the three types mentioned above can be further subdivided, according as the core has a smooth surface, or is provided with teeth projecting through the winding. The following table contains a list of the dynamos and motors commonly in use at the present day, classified under the six types as explained above :—

I A. *Drum with Smooth Core.*

Edison, made by the Edison Company.

Edison-Hopkinson, made by Messrs. Mather and Platt.

Parson, made by Messrs. Clarke, Chapman, and Co.

Thomson-Houston, made by the Thomson-Houston Company.

Siemens, made by Messrs. Siemens and Co., Limited.

I B. *Drum with Toothed Core.*

Weston, made by the United States Electric Lighting Company.

Immish, made by Mr. Moriz Immish.

Griscom, made by the Griscom Company.

II A. *Cylinder with Smooth Core.*

Manchester, made by Messrs. Mather and Platt.

Gramme, made by Messrs. Goolden and Trotter.

Elwell-Parker, made by Messrs. Elwell, Parker, and Co., Limited.

Marcel-Deprez, made by Syndicat Français d'Electricité.

Crompton, made by Messrs. Crompton and Co.

Maxim, made by Maxim-Weston Company.

Jones, made by Messrs. Greenwood and Batley.

Andrews, made by Messrs. Andrews and Co.

Kapp, made by Messrs. W. H. Allen and Co.

II B. *Cylinder with Toothed Core.*

Phœnix, made by Messrs. Paterson and Cooper.

Reckenzaun, made by Mr. Reckenzaun.

Brush, made by Anglo-American Brush Corporation.

III A. *Disc with Smooth Core.*

Schuckert, made by Mr. Schuckert.

Victoria, made by Anglo-American Brush Corporation.

New Gülcher, made by the Gülcher Company.

IIIB. *Disc with Toothed Core.*

Gülcher, made by the Gülcher Company.

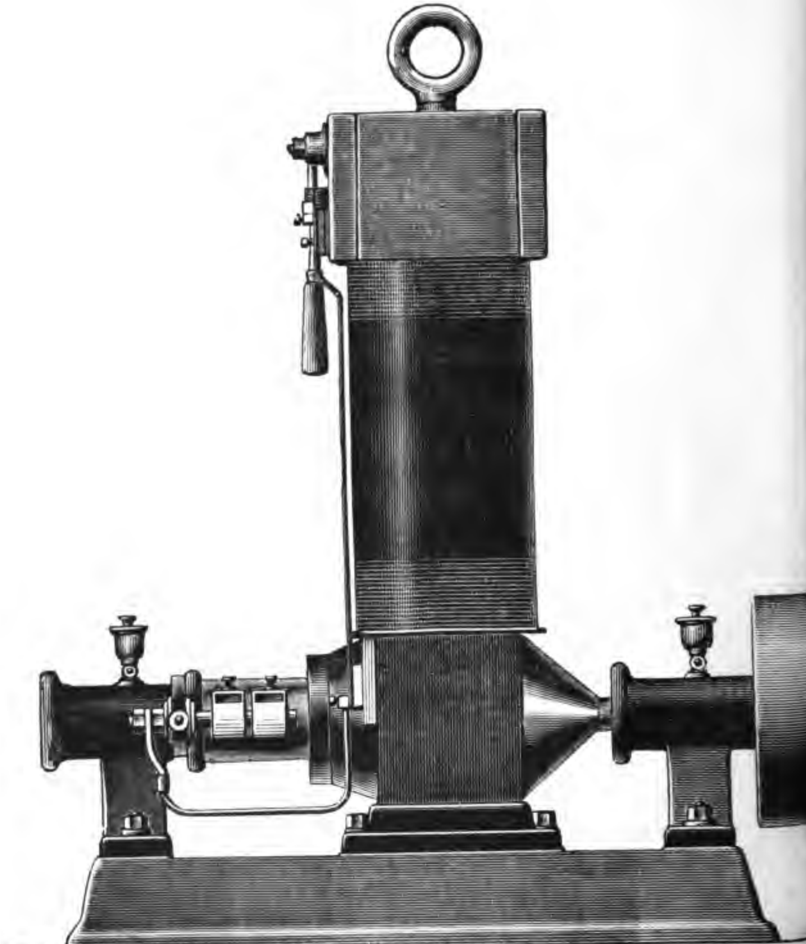
Joel, made by the Pilsen-Joel Company.

The core of the Edison armature consists of a number of circular iron discs threaded on the spindle, and held together lengthway by bolts and screws. The pole pieces are massive cast-iron blocks bored out to receive the armature. The field is produced by a compound magnet consisting of a number of long wrought-iron cylinders of comparatively small diameter, abutting at one end against the pole pieces and at the other against the yoke, which is a massive cast-iron block. It will be clear that this arrangement is defective on account of the high magnetic resistance occasioned by the small cross-sectional area of the magnet cores, and also because the total length of magnetizing wire required for a number of small magnets is greater than that which would suffice for a single magnet, the cross-sectional area of which is equal to the sum of the areas of the small magnets. Since the specific magnetic resistance of cast iron is considerably greater than that of wrought iron, the cast-iron part of a magnetic circuit should be larger than the wrought-iron part; and if this be not the case in any particular point—as, for instance, at the butting joint between magnet cores and pole pieces and yoke above mentioned,—the lines of force will be throttled at that point, thus reducing the strength of the field. Another defect in the Edison machine is that the bolts employed to hold the core of the armature together are not insulated from it, and become, therefore,

the seat of strong local currents, which create heat and absorb energy. Dr. Hopkinson has in his modification of the Edison dynamo removed the various defects here enumerated, and has produced machines giving for the same size of armature about double the output as compared to the Edison type. One of these improved dynamos is illustrated in Figs. 84 and 85. The iron discs forming the core of the armature are held together by two large washers screwed on the spindle, thus doing away with the bolts used by Edison. The field is formed by one single horse-shoe only, the core being 18 inches wide by $9\frac{1}{2}$ inches thick, with rounded corners. Area of core 171 square inches. The armature is 10 inches in diameter, and contains 80 conductors, or 40 complete turns, each conductor consisting of 16 strand ·069 wire. A stranded conductor is used in preference to a solid one, on account of the greater facility of bending and laying across the ends. The attachment to the commutator, which contains 40 bars of hard-drawn copper insulated with mica, is made with gold-plated spoons, which system insures good contact and at the same time admits of easy removal for the purpose of repairs. The resistance of the field magnet coils, which are coupled up as a shunt to the armature and external circuit, is 16 ohms, that of the armature is ·009 ohms, and at a speed of 800 revolutions a minute the electro-motive force is 110 volts, and the maximum current is 300 amperes. Similar machines, but wound for 250 volts, are used both for generators and receivers at the Bessbrook and Newry Electric Tramway, where the motive power is furnished by turbines.

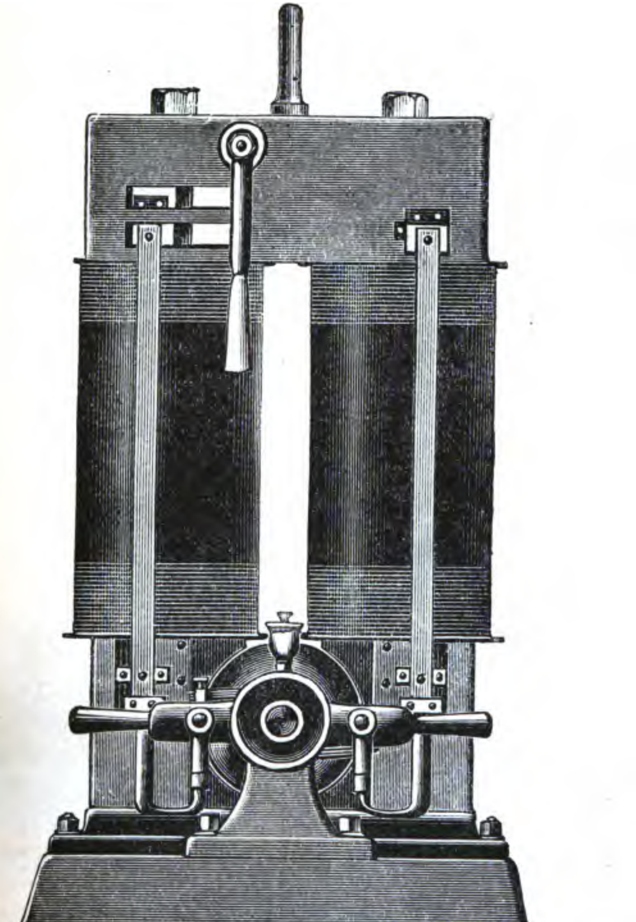
The *Thomson-Houston* machine seems, on account of its high electro-motive force, particularly suitable for

Fig. 84.



EDISON-HOPKINSON DYNAMO.

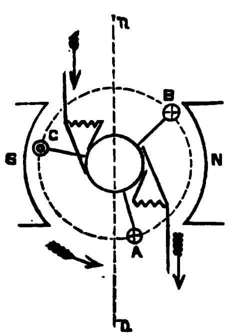
Fig. 85.



EDISON-HOPKINSON DYNAMO.

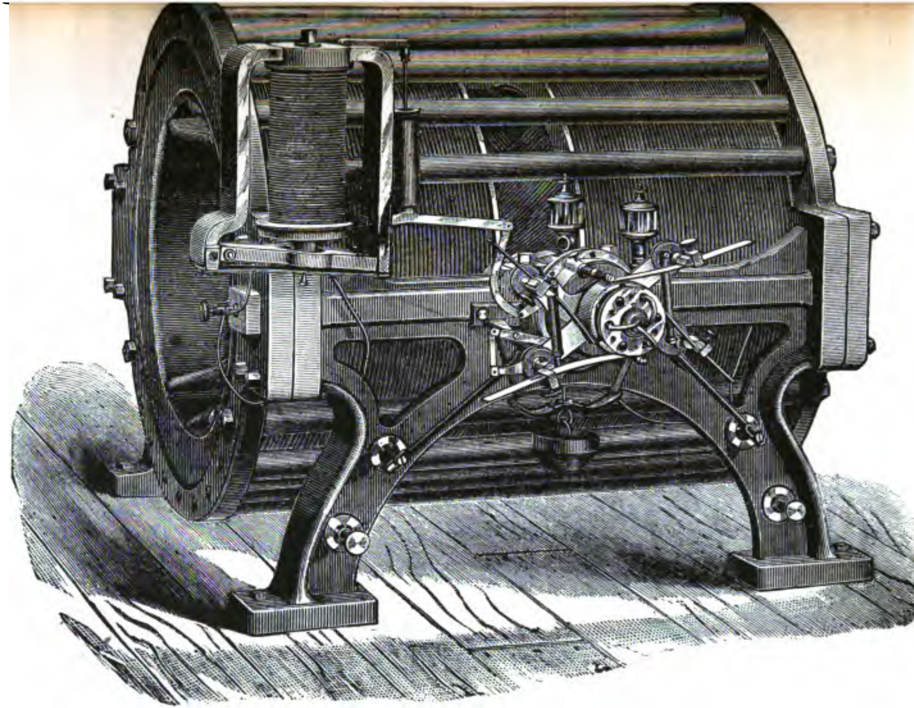
the transmission of energy over long distances. Fig. 87 shows a general view of this remarkable dynamo. The armature contains only three coils, but each of many turns wound over an ellipsoidal core consisting of an inner cast-iron shell and winding of iron wire. Since the copper coils are in planes containing the spindle, as in all drum armatures, the radial depth of the coils is greatest near the axle and least at the equator of the ellipsoid, thus bringing the external surface of the arma-

Fig. 86.



ture when completed up to a true sphere. The field magnet cores are short cylinders of cast-iron, provided at their outer ends with external flanges for connection with wrought-iron bars forming the yoke (see also Table of types of magnet, page 100), and at their inner ends with pole pieces forming the zones of a sphere within which the armature revolves.

The action of the machine will be understood by reference to Fig. 86, which represents diagrammatically the armature, commutator, brushes, and pole-pieces, *S N*. Since diametrically opposite points of the same coil pass



THOMSON-HOUSTON DYNAMO.

always before poles of opposite sign, the electro-motive forces created in those points are of opposite direction as regards a fixed point in space, but of the same direction as regards the coil itself. In considering the action of the armature, it will, therefore, suffice if we substitute for each coil one half turn of wire; the effect will be the same in kind, though, of course, reduced in magnitude. Let *A*, *B*, *C* represent the three half turns in end view. The coils themselves are wound in the following manner: The first half of coil *A* is wound, the starting end being left near the axis and free. To this is joined the starting end of coil *B*, and the first half of it is likewise wound, forming with coil *A* an angle of 120 degrees. The starting end of coil *C* is next joined to the two others, and the whole of coil *C* is then wound, forming with the two others an angle of 120 degrees. Coil *B* is next completed, and finally coil *A*, which finishes the winding. The three free ends of the coils are brought out through the hollow spindle, as shown in Fig. 87, and are attached to three segments of a commutator, each a little less than 120 degrees long, so as to leave an insulating air space between adjacent segments.

We assume in Fig. 86 that the lines of force pass straight across from one pole piece to the other. In this case *n n* will be a neutral line, and no electro-motive force will be created in any of the wires whilst passing it. To the right of that line the electro-motive force is directed towards the observer—the direction being indicated by a little cross inscribed into the circle representing the wire—and to the left of that line the electro-motive force is directed from the observer, the direction being indicated by a dot placed similarly. On each side of the neutral line there are fixed two brushes forming an angle of

about 60 degrees with each other, and being in metallic connection as shown. The current enters the armature by the brushes on the left, and leaves it by the brushes on the right. Since the commutator segments form an arc of nearly 120 degrees, it will be seen that *A* is placed in contact with the lower positive brush as soon as it has passed the neutral line, whilst *B* only leaves the upper positive brush a moment before it reaches the neutral line. Each coil is thus in contact with one or the other set of brushes for nearly one half revolution and two coils are connected in parallel for nearly a sixth part of a revolution, the third coil being during that time in series with them. When *B* has passed the neutral line it becomes connected in parallel with *C*, and *A* is in series with them. The next sixth of a revolution brings *C* and *A* into parallel and *B* into series connection, and so on. It might be thought that on account of the small number of coils on the armature the current must be pulsating. This, however, is not the case, and the steadiness of the current is partly due to the fact that each coil, when it is in the position of strongest action, is coupled with the two other coils, which are in the position of weakest action, and partly to the effect of self-induction in the field-magnet coils, which are in series with the armature and external circuit. The magnetic inertia of the field opposes a certain passive resistance to any sudden change in the intensity of the current and acts as a steadying agent in the same manner as a heavy fly-wheel on a steam-engine tends to keep the speed uniform. Self-induction plays also an important part in the armature itself, preparing, as it were, each coil for the current which is generated in it as soon as it passes the neutral line, and yet preventing any undue amount of back flow

of current through any single coil whilst the same is in a weak part of the field. It is evident that in a symmetrical field the electro-motive forces in *A* and *B* will be equal at the moment when these wires are equidistant from the neutral line, but not in any other position. When *A* has advanced into a position where its rate of cutting lines of force is greater, *B* will have advanced into a position where its rate of cutting lines of force is less than before, and consequently the electro-motive forces in these two coils (which, as mentioned above, are in parallel connection) will no longer be equal. If there were no self-induction in *B* the excess of electro-motive force in *A* would simply be used up in urging a local current through the two coils. This current would be quite useless as far as the external circuit is concerned, and the energy thus wasted would, of course, result in a reduction of the available electro-motive force. In reality this is not the case. The coil *B*, although of lower electro-motive force than *A*, is able by its self-induction to resist for a certain time the current which *A* tries to force back through it. This resistance can only last a very short time, after which, figuratively speaking, *B* would be overpowered by *A*; but the time during which the two coils are coupled parallel is also exceedingly short. In a machine running at 850 revolutions a minute it would only require the one hundred and seventieth part of a second for the wire *B* to move from a position where it is equivalent to *A* into a position where it is already disconnected from *A*. Small as this interval of time may appear, it suffices for the creation of some, though not a very large back current in *B*. This is an advantage, for when *B* has passed the neutral line it becomes coupled in parallel with *C*, and could, therefore, receive a strong

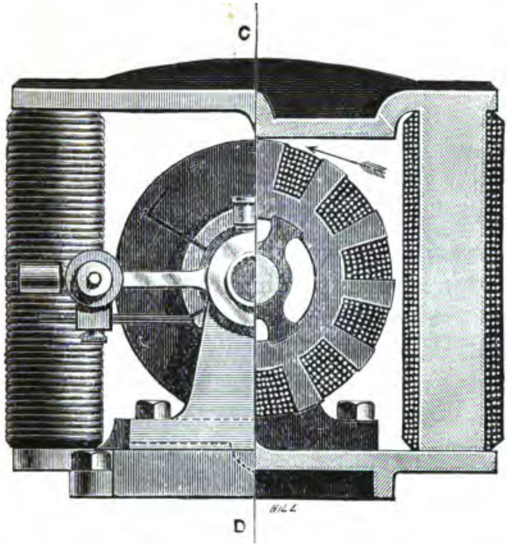
local current from the latter coil, which at the time is near its position of best action. But since *B* has been provided by *A* with a downward current before passing the neutral line, the inertia of this current and the self-induction of the coil *B* are sufficient to resist for a short time the tendency of *C* to set up a back current. By the time this resistance could be overcome coil *B* itself has passed into a strong part of the field and has thus become the seat of a high electro-motive force. A moment later *C* enters the weak part of the field, and is charged by *B* with an upward current, preparing it for parallel connection with *A* on the right of the neutral line, and so on. It cannot, of course, be expected that these inter-actions take place with mathematical precision, and that the forces be balanced to a nicety, and it is, therefore, necessary to make provision by which any want of balance, manifesting itself in sparking at the commutator, may be rendered harmless. For this purpose an air blast is fitted to the machine, the jets of air being directed at the two points on the commutator where the forward or leading brushes touch it, and the action of the blast, which is intermittent, is so timed that a puff of wind is produced at each moment when a segment leaves the brush, thus blowing out the spark.

The machine is made self-regulating for constant current by an electro-magnetic device (shown on the left in Fig. 87), which causes the angle between each set of brushes to increase when the current becomes too strong, whereby the armature is for shorter or longer periods short-circuited on itself, and its electro-motive force withdrawn from the external circuit. A detailed description of the mechanism employed will be found in an article by the author, published in "The Engineer" for August 28,1885.

Passing now to machines having drum armatures with toothed core, that of most direct interest to our subject is the *Immisch electro-motor.* It has already been pointed out that the current passing through the coils of any armature tends to develop magnetic polarity in the armature core, and the torque of the armature can be considered to be the effect of the attraction and repulsion between the poles of the field-magnets and those developed in the armature. Since the armature poles depend on the armature current, this explanation is identical with that given previously, where it was stated that the torque is proportional to the product of strength of field and armature current. In the Immisch motor an attempt has been made to avoid to some extent the magnetic induction between like poles in armature and field, and to increase the induction between unlike poles by the device of recessing part of the pole pieces, as shown in Fig. 88. On theoretical grounds no advantage can be expected from this design; and, indeed, it is inapplicable to cases where the motor is required to run in either direction. If this condition has to be fulfilled, the pole pieces are bevelled off on both sides, as shown in the half-section, Fig. 89. The pole pieces are extended in a direction parallel to the armature spindle, as will be seen from the perspective view, Fig. 90.

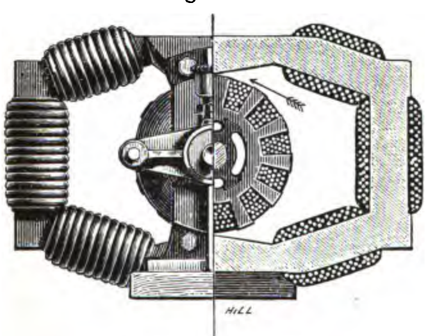
The principle underlying Immisch's motor is that the number of armature coils shall be greater or less by one than the number of field poles. Thus an armature with three coils can be employed in either a two-pole or a four-pole field; an armature of five coils can be employed in a four or six-pole field, and so on. On account of simplicity, however, the usual arrangement is a three-coil armature in combination with a two-pole field. The

Fig. 88.



IMMISCH MOTOR.

Fig. 89.

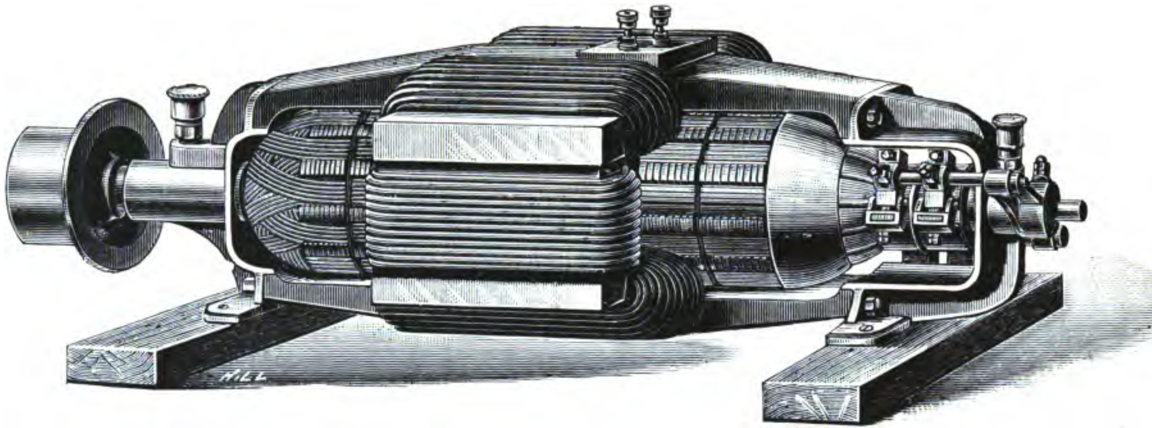


IMMISCH MOTOR.

core of the armature is built up of toothed iron discs, supported on gun-metal arms, and separated from each other by paper insulation, and further divided into groups so as to form three or more air-spaces. Openings are left between the layers of wire crossing each other at the ends, so that air can enter into the space surrounding the spindle; and openings are also left between the winding on the outer surface. As far as the author knows, this is the only drum armature with internal ventilation. The six ends of wire corresponding to the three armature coils are connected to a commutator consisting of two series of three segments each. The two series have an angular displacement with regard to each other, so that the dividing line between two segments in the first series stands opposite the middle of a segment in the second series, and *vice versâ.* Brushes resting on the commutator at opposite points, and overbridging both series, connect two of the coils in parallel circuit, while the third coil is cut out. The two active coils form poles on that part of the armature which is surrounded by the third or inactive coil. Since the latter could, by reason of its position, not contribute anything to the intensity of these poles, the fact of its being cut out does not in any way diminish the torque, but it has the advantage of reducing the resistance of the armature by one-third. By splitting up each brush into two separate brushes, the two active coils can be connected in series, thus rendering the same motor suitable for double the electro-motive force. In many cases this is an advantage, and the change can be effected by means of a simple switch.

One of these motors, as tested by the jury at the recent Inventions Exhibition, gave the following results:—

Fig. 90.



IMMISCH MOTOR.

Speed.	Volts.	Amperes.	Brake H-P.	Commercial Efficiency.
1,240	40	19·0	·794	·778
1,500	49	19·5	·960	·750
1,800	58	19·5	1·150	·761
2,100	68·5	27·0	1·340	·732
2,100	69·9	20·0	1·340	·719
2,220	84	27·0	2·308	·759
2,320	90	26·0	2·413	·771
2,400	93·5	27·0	2·496	·733

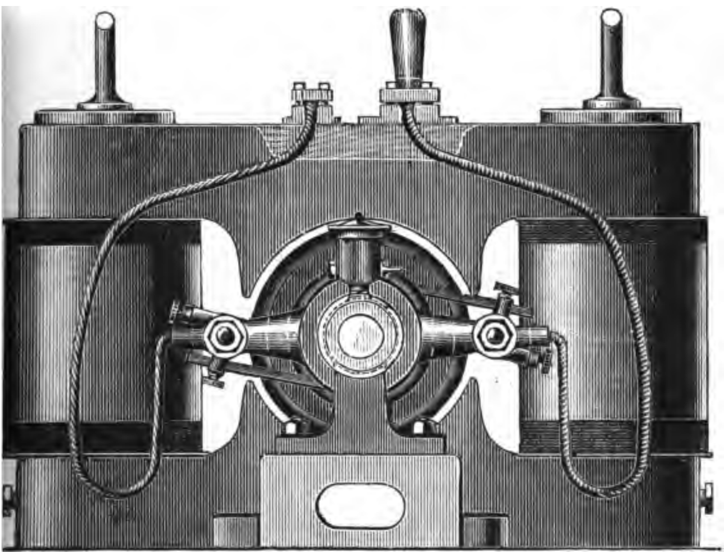
The weight of the motor tested was 156 lbs., being at the rate of 62 lbs. per horse-power for full load. The following is a table containing diameter of armature, extreme load, and weight as given by the maker:—

Armature	4″	5″	6″	7″	8″	9″	10″
Extreme load, h-p.	1·5	3·25	6·7	12·5	19	26	35
Weight, lbs.	80	156	270	430	640	910	1,250

Amongst the machines with smooth cylindrical armature cores the "*Manchester*" dynamo deserves special mention for its compact form. It will be seen from the illustration, Fig. 91, that the magnetic circuit is of the double horse-shoe pattern, the magnetizing coils being placed over that portion of the magnet which in other machines constitutes the yoke. The pole pieces are heavy cast-iron blocks, the lower one being provided with extensions for carrying the bearings of the armature spindle. The magnet cores are wrought-iron cylinders, and their ends are fitted tightly into extensions of the pole pieces. The area of contact between the cast-iron and wrought-iron portions of the magnetic circuit is about twice as large

as the cross-sectional area of the magnet core, in order that the lines of force in passing from the material of greater magnetic conductivity into that of smaller magnetic conductivity may not be throttled, as was the case in the original Edison dynamo. The armature core con-

Fig. 91.



MANCHESTER DYNAMO.

sists of a series of thin wrought-iron discs insulated from each other at their outer periphery, and supported on the spindle by metal arms in a positive mechanical manner. The wire coils are, however, held on the core by friction only, which is increased by the presence of the usual binding hoops. The electrical data of a machine intended for a current of 200 amperes at 110 volts pressure, as given by "The Engineer" for Aug. 7, 1885, are as

follows:—Magnet cores, $7\frac{1}{2}$ inches diameter; length of magnetizing coils (which are wound on separate metal sleeves), $12\frac{1}{2}$ inches; armature core, 12 inches diameter and 12 inches long; armature conductor, 203 mils solid wire wound in 120 convolutions, and connected in the usual way with a 40-part commutator; resistance of armature, ·023 ohms; field magnets are compound-wound; resistance of shunt coils on magnets, 19·36 ohms; resistance of main coils on magnets, ·012 ohms; each magnet limb contains 1,680 turns of 65 mils shunt wire, and 42 turns of treble 203 mils main wire; normal speed, 1,050 revolutions a minute. There is no provision made for ventilating the interior of the armature core.

The core of the *Elwell-Parker Armature* consists of iron wire coiled direct upon two sets of metal supporting arms. To preserve a true circular shape segments of wood are inserted between the arms, and the outside is turned to a cylindrical surface before the iron wire is coiled on to it. The outer edges of the arms are insulated with tape and fibre, so as to prevent contact between the arms, which are keyed to the spindle, and the core or the copper conductor. In Fig. 92[1] *a*, *a* are the two sets of arms keyed to the spindle *C*, and having on each side projections *e*, by which stout fibre washers, *d*, are held in place. The object of these washers is to hold together lengthways the coils of iron wire (partly shown in the illustration) which form the armature core. After the same is completed, the wood segments are removed, and the copper conductor is wound over the core, and connected with a commutator in the usual Gramme method.

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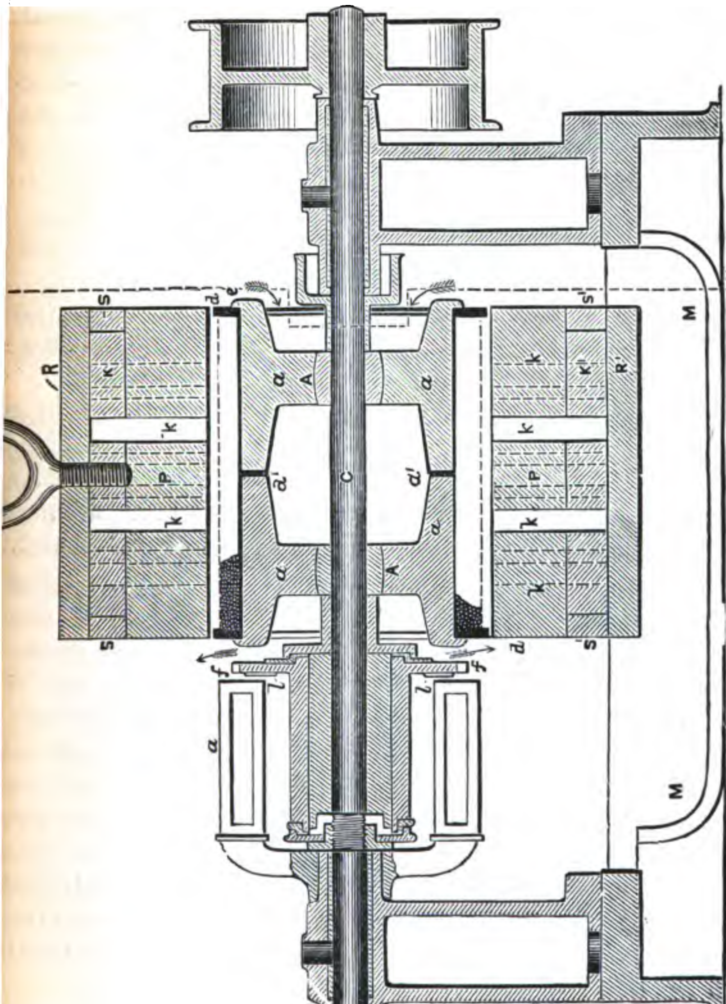
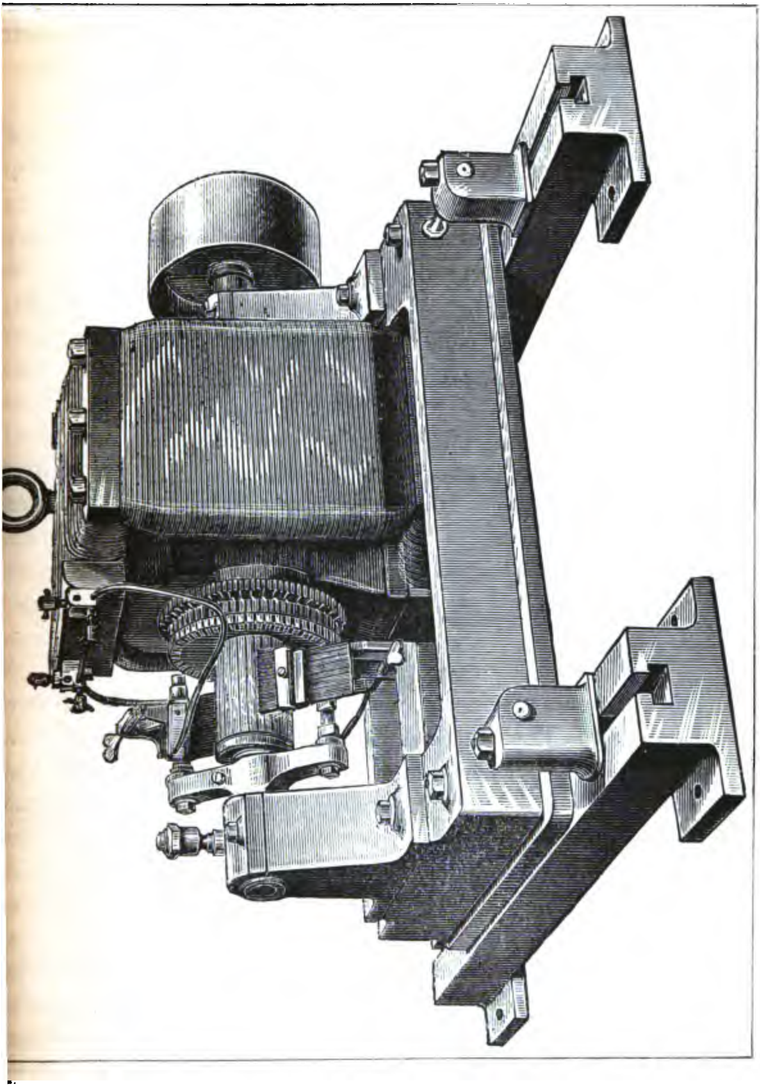
[1] The author is indebted to the courtesy of the editor of "The Engineer" for this illustration, as well as for Figs. 86, 96, 97, 98, 101, 108.



ELWELL-PARKER DYNAMO.

The bars of the commutator are provided with long tags *f*, which serve to support a leather disc *l*, by which means air is prevented from being drawn into the interior of the armature from the side of the commutator. Were this precaution not adopted, copper dust produced by the wearing of the brushes would be drawn by the current of air into the armature, and lodging between the internal coils, would sooner or later create a short circuit. The tags *f* act as fan-blades, expelling the air at the left, and drawing it into the armature at the right, thus not only ventilating the internal coils, but also keeping the copper-dust out. The interior of the core itself is, however, not ventilated. The conductor is wound over the core in one layer only on the external surface in order that the distance between the core and pole pieces and, therefore, the magnetic resistance of the air space (see Chapter IV., page 108) may be a minimum.

The field magnets are formed by four slabs of wrought iron bolted together at the corners so as to form a rectangle, as will be seen from the perspective illustration, Fig. 93. In the longitudinal section (Fig. 92), *S*, *S* represent the cores proper of the magnets, and *K*, *K* are cast-iron pole pieces bolted on. To increase the magnetic conductivity a number of holes are drilled through the cast and wrought iron, and soft iron pins (shown in dotted lines) are tightly driven into these holes. In some of the later machines the pole pieces themselves are made of wrought iron, and then there is no need of this device. The field magnets are supported on a frame, *M*, of non-magnetizable metal, which also serves as a base for the bearings of the armature spindle. This machine acts equally well as a dynamo or as a motor, but where economy of space is an object, as for instance in motors

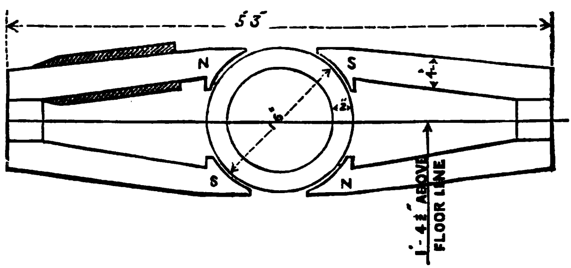


ELWELL-PARKER TWO-POLE DYNAMO OR MOTOR.

for tramways, which must be placed under the floor of the car, field magnets of the Siemens type (see type of magnets, page 100) as shown in Fig. 96 are employed.

In dynamos of larger size the field magnets are so arranged as to present four poles to the armature, Fig. 94; two diametrically opposite poles being of the same sign. In this manner four distinct circuits through the armature are obtained, and correspondingly four brushes are used. If equi-potential points of the armature conductor

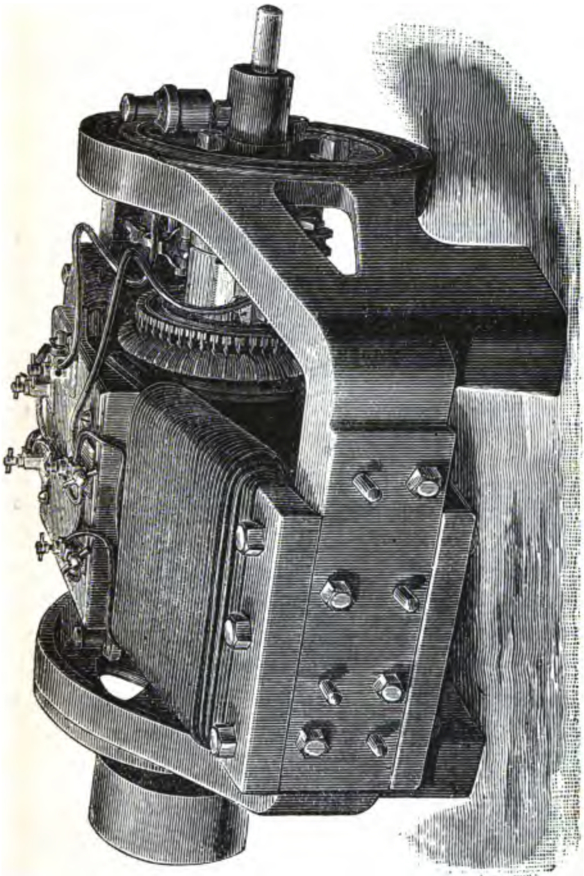
Fig. 94.



FOUR-POLE MACHINE.

were permanently connected with each other, as has been done in the Elphinston-Vincent and in the Victoria dynamos, two brushes would suffice. The practical advantage of four poles over two is that double the current can be obtained without increasing the density of current in the armature conductor. On the other hand, there is a slight sacrifice of electro-motive force due to the greater magnetic resistance of air space and consequent weakening of the field. In cylinder armatures the area of each pole piece (λ b of the formula given in Chapter IV.) must evidently be the smaller, the more separate pole pieces have to be placed round the armature, and, consequently,

Fig. 96.

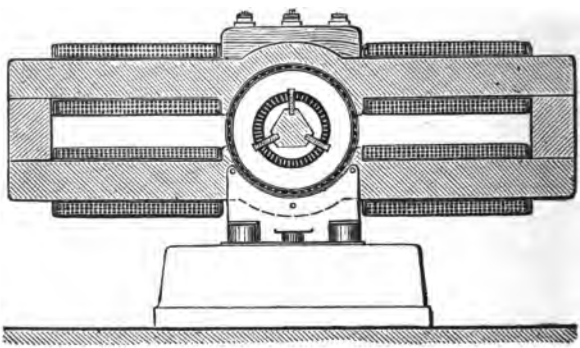


ELWELL PARKER MOTOR.

the four-pole machine must have considerably more magnetic resistance than a two-pole machine of equal size.

The illustration, Fig. 95, shows the latest type of these dynamos, which are supplying current for the Blackpool Electric Tramway. They are each wound for a current of 180 amperes, and at 350 revolutions a minute their electro-motive force is 200 volts, which is found to be

Fig. 97.



CROMPTON DYNAMO.

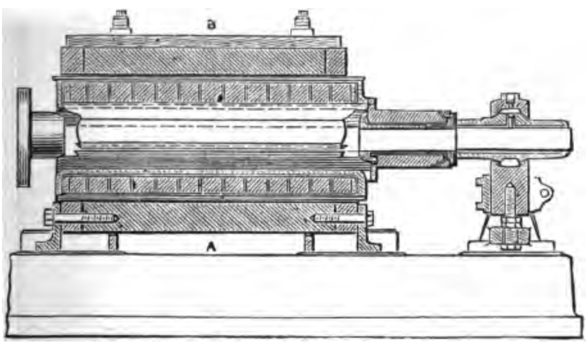
sufficient for the working of the line. The field magnets are separately excited by a small dynamo of the type shown in Fig. 93, and the same size of armature, but in combination with Siemens field magnets, is used in the motors on the tramcars. Fig. 96 gives a perspective view of this motor.

The dynamo and motor employed by M. Marcel Deprez in his experiments on the transmission of energy, also belong to the class of machines under consideration, and should therefore be described in this place. But since the practical importance of these experiments renders it necessary to describe them in some detail, the author has

ught it best to defer the description of the machines to apter XII., where the subject is treated as a whole.

The core of the Crompton armature consists of a num- of thin wrought-iron discs, about 25 to the inch, ooth on the outside, but provided on the inside with e or more dovetail notches placed equidistantly; and the grooves thus formed radial bars are fitted, as l be seen from Fig. 97, which is a cross-section through

Fig. 98.

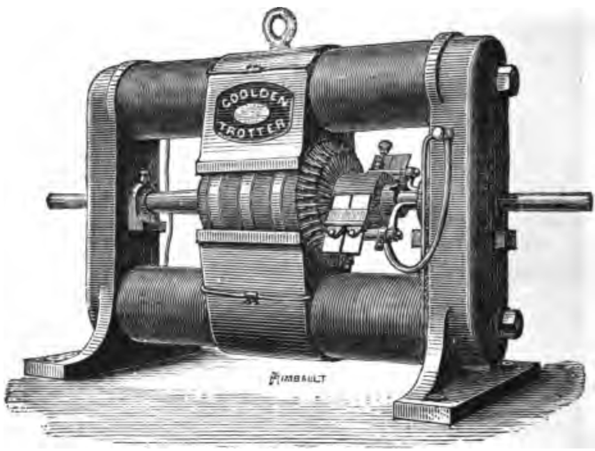


CROMPTON DYNAMO.

1,000 Watt Crompton dynamo. Fig. 98 is a longi- dinal section. The inner edges of the radial bars are ted into grooves slotted out in the steel spindle, the cross- ction of which is triangular, so as to afford sufficient pth of grooves without weakening the central portion of e spindle. Each alternate disc is coated on both sides th insulating paint, and at stated intervals fibre dis- nce pieces are inserted by which the core is subdivided to a number of comparatively narrow rings, the object ing to afford passages for air through the body of the re to cool it. These divisions are shown in Fig. 98.

The field magnets are of the double horse-shoe pattern, and consist of straight wrought-iron slabs bolted together at the yokes, and attached to a cast-iron bedplate by gun-metal chairs. In the machine here illustrated, and in fact in all machines of large size, the armature is wound, not with wire, but with square bars of copper. The elec-

Fig. 100.



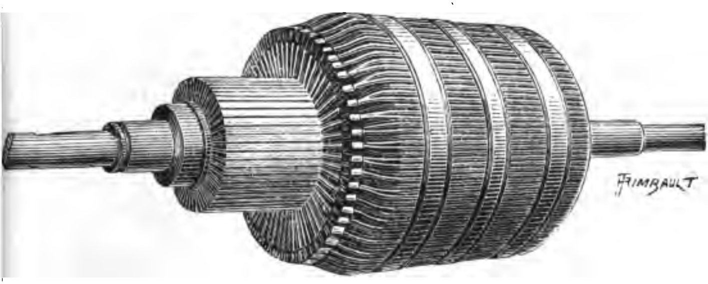
GOOLDEN AND TROTTER DYNAMO.

trical data of this machine, as given by "The Engineer," are as follows: Core of armature 12 inches diameter, $2\frac{1}{2}$ inches deep, and 28 inches long; air space between core and pole pieces ·47 inches; core of field magnets $4\frac{1}{2}$ inches thick by 24 inches wide; conductor on armature 300 mils by 180 mils, wound over the core in 120 turns, and connected in the usual way to a 60-part commutator; resistance of armature ·021 ohms. The machine is intended for a current of 200 amperes, and at 450 revolutions the electro-motive force is 110 volts. Fig. 99 shows the

arrangement adopted by Messrs. Crompton for driving these dynamos direct by Willans' high-speed engines. To get the centre of rotation low, a point of importance in ship lighting, the dynamo is placed horizontally as shown in these illustrations, but where there is sufficient overhead room a vertical arrangement may be used.

The *Goolden and Trotter Dynamo*, shown in Fig. 100, differs from the original Gramme machine only in its more substantial mechanical design. The side pieces of the frame are made sufficiently heavy to serve as efficient

Fig. 101.



GOOLDEN AND TROTTER ARMATURE.

yokes, and the armature core, which consists of charcoal iron discs, is secured in gun-metal arms, by which the driving power is transmitted to the core in a positive manner. The copper winding, however, is held by friction only, Mr. Trotter being of opinion that an attachment by friction pure and simple is perfectly reliable.[1] The complete armature is shown in Fig. 101.

The Andrews dynamo is remarkable for a peculiar method of connecting up the coils. It is a four-pole ma-

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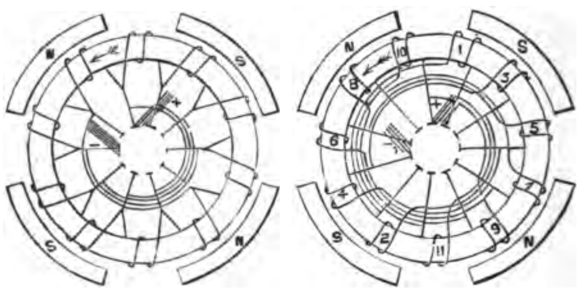
[1] See "Proceedings of Institution of Civil Engineers, Session 1885-86." Discussion on the author's paper on "Dynamos."

chine with two brushes only, but diametrically opposite, and therefore equipotential points of the conductor are not connected in the usual way so as to split up the winding into four parallel circuits from which double the current can be obtained. In this case the connections are made in such a way as to obtain the same current, but double the electro-motive force. The difference will best be understood by reference to Fig. 102, which shows both

Fig. 102.



systems side by side, that on the left being the coupling for quantity, that on the right the coupling for tension. In the latter system an uneven number of coils must be employed, generally fifty-nine, but for clearness of illustration only eleven are shown. One end of each coil is connected to its commutator-plate and the other to the wire connecting the opposite coil with its communtator-plate. Thus the front end of 1 is connected to the back end of 2, and to plate 2 of the commutator, the front end of 2 is connected to the back end of 3, and to plate 3, and so on, the last connection being the front end of 11 to the back end of 1 and to plate 1. The current entering the armature at the negative brush, where it touches plate 6,

splits into two circuits, one going round coil 6, up on the outside of the armature, the other round coil 5, down on the outside of the armature. The former current goes successively up in 7, 8, and 9, leaving the armature at plate 10 by the positive brush, whilst the latter goes successively down in 5, 4, 3, 2, 1 and 11, leaving the armature also at plate 10. If there were 59 coils the current would go similarly up in 28, and down in 31 coils, and by following the direction of the current in the diagram it will be seen that it is the same as the electromotive force induced in each coil—in other words, that the electro-motive force created by one pair of poles is added to that created by the other pair.

The author's dynamo, intended for very low speeds, is shown in the perspective illustration (Fig. 103), coupled direct to a double-acting twin-engine. The core of the armature consists of iron wire coiled upon a supporting cylinder of gun metal, which in its turn is keyed to the spindle by two sets of arms. The cylinder is provided with flanges partly for the purpose of stiffening it, and partly for the purpose of subdividing the body of the core into a number of comparatively narrow rings. The surface of the cylinder is perforated, and air can enter through the perforations into the annular spaces formed between adjacent flanges, and escape at the outer periphery, since the latter is not completely covered by the external coils. The flanges are provided with radial extensions or "driving horns," which are tipped with fibre ferrules, and enter between the external coils for the purpose of transmitting the driving-power to the copper conductor in a positive, mechanical manner. This precaution is the more necessary as at the low speeds employed the field must be exceptionally strong in order

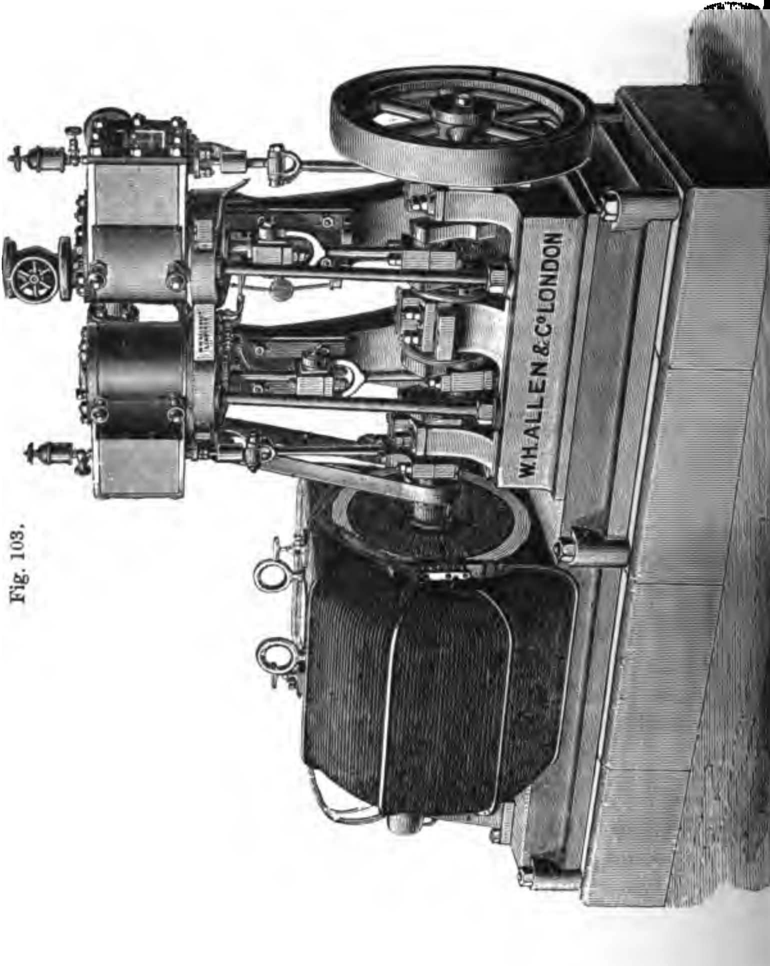
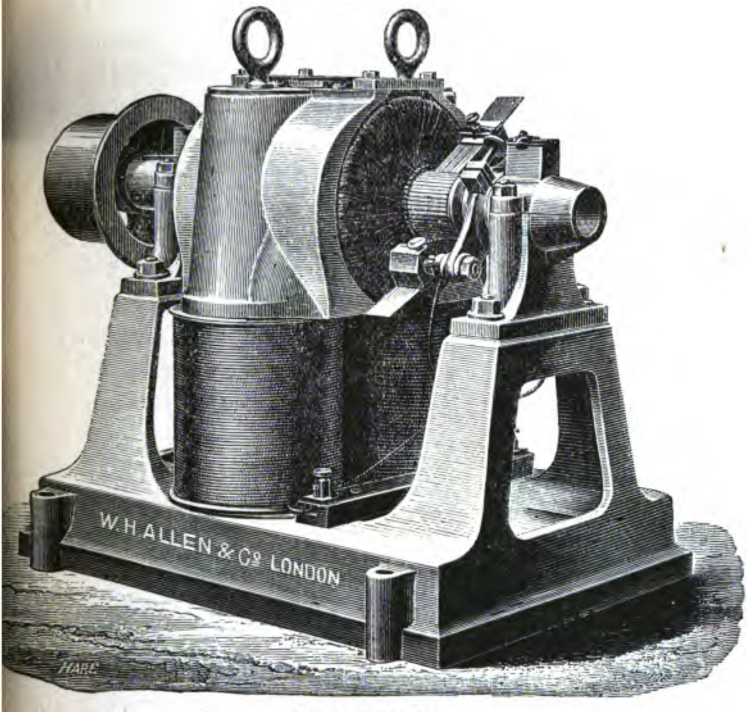


Fig. 103.

that the desired electro-motive force may be produced, and the stronger the field, the greater is the magnetic drag exerted by it on the armature wire. In many

Fig. 104.



KAPP DYNAMO.

machines the friction produced by the external binding-hoops is alone relied on to carry the wires through the field; but experience has shown this to be insufficient. Even if the wires are not bodily torn off the armature by the magnetic resistance of the field, they shift and work on the surface of the core; and it is only a question of

time when the insulation will be destroyed, and the machine break down.

Fig. 103 shows a type of field magnets which has been chosen with a view to obtain a maximum magnetic effect with a minimum weight of material. Where a reduction of weight is not of paramount importance the author employs a single horse-shoe magnet of the type shown in the table at page 100. The dynamo here illustrated gives a current of 170 amperes, at a pressure of 110 volts when worked at 340 revolutions a minute. Its weight complete with engine and base-plate is 3 tons

The author's high-speed dynamo for belt-driving is shown in Fig. 104. Its armature is constructed on the same principle as that above described, but the field magnet is different. It is a single horse-shoe with cylindrical limbs of soft wrought-iron, the cast-iron bedplate forming the yoke. The upper end of each core is turned to a cone on which is fitted a cast-iron pole piece, intimate contact between the two being secured by the pressure of the top screw eye-bolt forcing the pole piece well on to the cone. As results from the theoretical considerations in Chapter IV., the single horse-shoe magnet requires less wire, and a smaller expenditure of exciting energy than a double horse-shoe magnet.

Amongst the armatures with toothed core, the oldest is Professor Pacinotti's. A more recent form, viz., that devised by Mr. Brush, must also be reckoned to this type; but since both these have already been illustrated and described in another volume of this series,[1] it will be best to pass them over, and describe one or two of the latest cylinder machines with toothed core.

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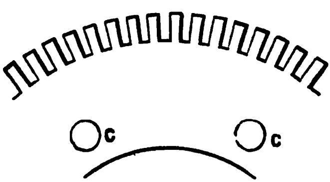
[1] The Specialist Series. Magneto and Dynamo Electric Machines.

The core of the "Phœnix" dynamo is built up of toothed wrought-iron discs, held together by bolts, *C C*, (Fig. 105), which project on each side, and serve also for attachment to the spindle by means of two gun-metal star wheels. The discs are insulated from each other, and also from the bolts. In a machine for an output of 42,000 watts, the core of the armature is $22\frac{1}{4}$ inches in external diameter, 9 inches long, and $4\frac{1}{2}$ inches deep radially. The notches form forty-two longitudinal grooves, each containing two coils side by side. The conductor is a

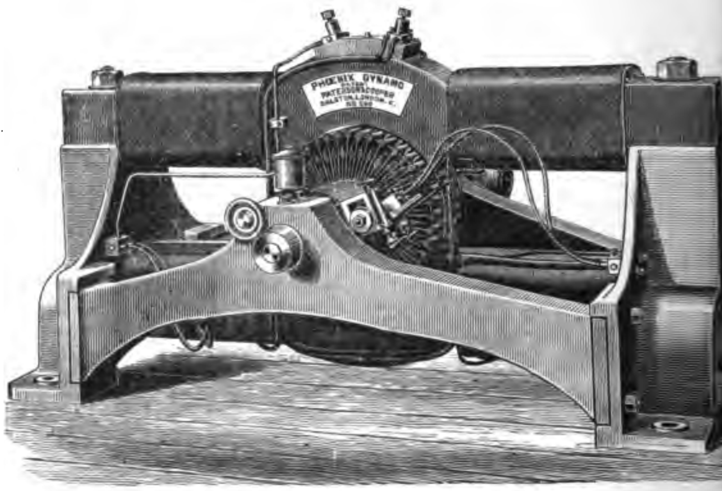
Fig. 105.



cable containing fifty 48 mils diameter wires, which is, of course, more flexible and easier to wind than a solid wire of the same sectional area. At 500 revolutions a minute the electro-motive force is 110 volts, and the current 380 amperes. The field magnets are of the double horse-shoe type, and the cores consist of bars of soft iron, 9 inches square, and 7 feet 6 inches long. Heating of the pole pieces is prevented by making the clearance between the teeth of the armature and the surface of the polar cavity sufficiently large, also by employing a comparatively large number (forty-two) of teeth, thus minimizing the magnetic reaction of each tooth on the pole pieces. Fig. 106 shows a perspective view of this machine.

The Reckenzaun motor has double horse-shoe magnets of wrought iron, in shape somewhat resembling De Meritens' arrangement, shown in the table at page 100. The core of the armature is composed of wrought-iron links (Fig. 107), with projections, *t*, which approach closely to the polar surfaces of the field magnets. The links are

Fig. 106.

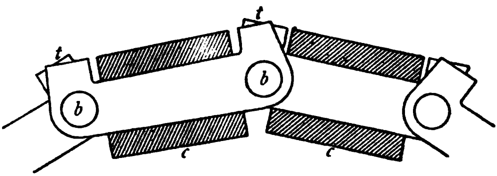


PHŒNIX DYNAMO.

stamped out of thin soft sheet iron, and are connected into a kind of chain by means of the bolts, *b*, which extend throughout the length of the armature, and serve at the same time for attaching it to two gun-metal star wheels by which it is keyed to the spindle. It will be noticed that the ventilation of an armature core of this form is very perfect, and the Reckenzaun armature has this further advantage —that, by drawing out one of the bolts, the core can be opened out into a straight line, thus greatly facilitating

the winding of the coils, *c*. When all the coils are wound, the two ends of the link chain are brought together, and secured by their bolt, when the armature is ready to be attached to the spindle. Owing to its peculiar construction this motor is extremely light, as compared to the power it can develop. In regular work about one

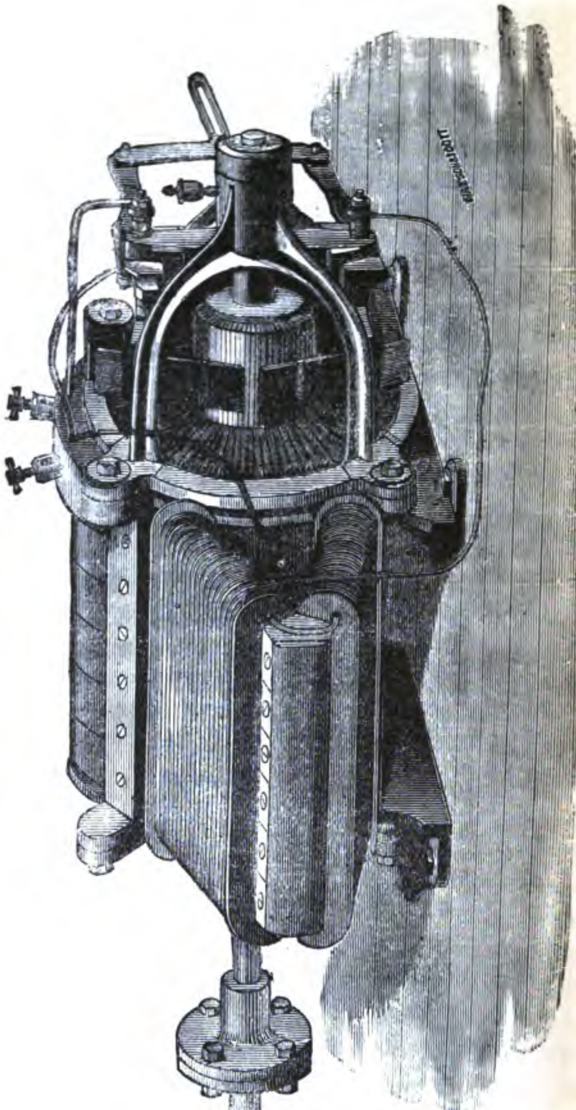
Fig. 107.



RECKENZAUN'S ARMATURE.

horse-power can be obtained for every 60 lbs. of total weight of motor. The following table, abstracted from a paper by Herr Zacharias, in the "Elektrotechnische Zeitschrift" of January, 1886, contains the results of dynamometric experiments made with a Reckenzaun motor of 124 lbs. total weight. This motor is illustrated in Fig. 108.

Fig. 108.



RECKENZAUN MOTOR.

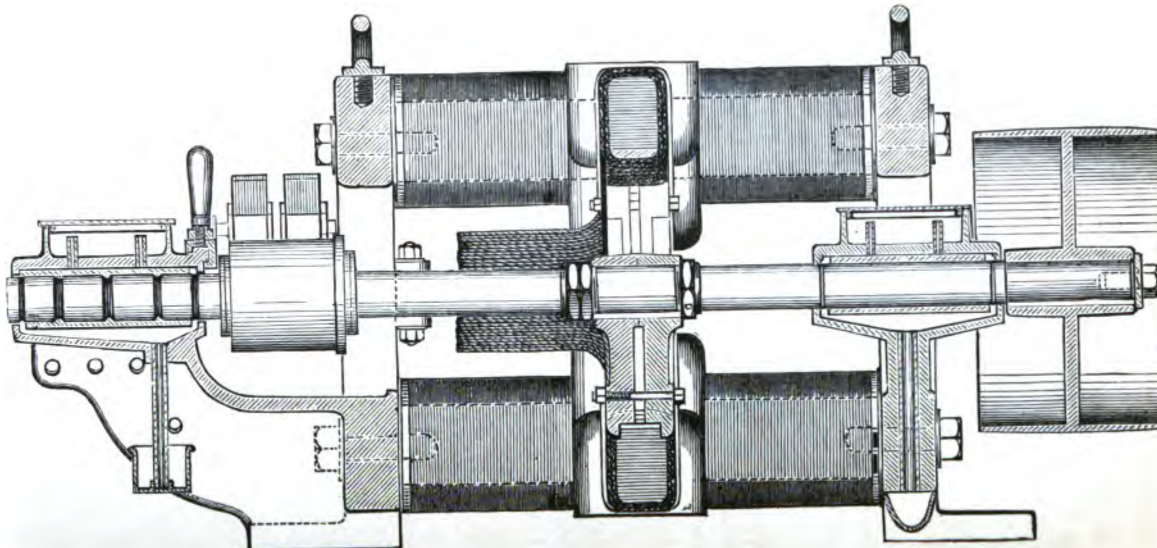
Reckenzaun Motor (total weight 124 *lb.).*

Revolutions per Minute.	Current.	Electro-motive Force.	Brake Horse-power.
1356	25·1	110	1·85
1458	22·4	110	1·72
1594	19·2	110	1·59
1782	16·5	109	1·45
1938	13·3	110	1·23
2092	10·0	110	1·14
1484	25·9	122	2·20
1751	22·2	122	1·94
1856	19·0	122	1·86
1980	16·0	122	1·60
2105	13·1	123	1·49
1730	25·2	135	2·36
1806	21·2	134	2·13
1936	19·2	133	1·94
2078	16·0	133	1·76

These motors have been largely applied to the propulsion of electric launches and electric tramcars.

The armature core of the *Victoria Dynamo*, a longitudinal section of which is shown in Fig. 109, consists of a wrought-iron ring upon which is coiled a spiral of No. 30 *B. W. G.* charcoal iron tape, the convolutions being insulated from each other by a tape of equal width of insulating paper coiled together with the iron tape. About one-seventh of the gross area of the core is occupied by this insulation. Although the iron tape is excessively thin, there is still a tendency to heat, which can only be explained by the circumstance, that on the outer periphery, where the lines of force are at right angles to the axis, they pierce the tape on its broad surface, and thus

Fig. 109.



VICTORIA DYNAMO.

cause it to become hot. To mitigate the evil radial grooves are turned into the core from the outside, thus subdividing the wide tape into a number of narrow strips. The core is supported by five gun-metal arms, each arm consisting of two halves, which are clamped together by screw-bolts, and to make the fastening more secure, slots are cut out of the wrought-iron ring and part of the core into which the extremities of the arms enter. In the dynamo here illustrated the core contains 7·8 square inches of iron in cross-section, and it is wound with 60 coils of 165 mils wire, each coil consisting of 6 turns. Total number of turns 360. The machine gives a current of 150 amperes at 75 volts pressure when running at 800 revolutions a minute.

The Gülcher Dynamo is very similar to the Victoria in general arrangement, but differs from it in the way the core of the armature is constructed. In the "Gülcher," which is the earlier machine of the two, the core consists of a malleable iron ring of H-section, provided with external Pacinotti projections, which, for purposes of ventilation, are perforated. Flat iron washers are laid on either side of the central web, between the top and bottom flange of the H-shaped ring, which are kept a small distance apart by insulating pieces, and are also perforated to admit air to the interior of the core. In this arrangement those lines of force which enter the core in a direction more or less parallel to the spindle, pierce the iron washers on the broad surface and cause them to heat. To remedy this evil, the original design has been altered by employing a ring of T-section, the head of the T being directed towards the centre, and iron tape being coiled on either side of the middle web. When the winding of the

tape is completed, the outer periphery of the core is turned in a lathe to a semicircular section. In this manner only the edges of the iron tape, but not its broad surface, are presented to the lines of force, and thus heating is avoided.

CHAPTER XI.

Historical Notes—Fontaine's Discovery—Figuier's Explanation—Early Patent of Pinkus—Early Electro-Motors—Page's Electric Railway—Ploughing by Electricity at Sermaize—Electric Cranes—Ventilating and Pumping by Electricity—Modern Electric Railways—Different Systems—Comparative Merits of Battery System and Conductor System—The Bessbrook-Newry Electric Railway—The Blackpool Electric Tramway—The Telpher Line at Glynde—Reckenzaun's Electric Tramcar—Comparative Estimates for Horse Traction and Electric Traction.

THE discovery of the principle that mechanical energy may be transmitted over considerable distances by the employment of two dynamo machines and a conductor, is commonly ascribed to M. Hippolyte Fontaine, who has in a recent pamphlet[1] given a detailed account of the way he was led to make the invention. Since the matter is now of historical interest, an abbreviated translation of M. Fontaine's account is here given. M. Hippolyte Fontaine says:—

"On the 1st of May, 1873, the International Exhibition in Vienna was formally opened, although the machinery hall, which was as yet incomplete, remained closed until the 3rd of June. I was engaged with the arrangement of a series of exhibits, then shown for the first time in public. There was a Gramme dynamo for electro-plating, capable of delivering 400 amperes at

[1] "Transmissions Électriques," by Hippolyte Fontaine. Baudry & Cie, Paris.

25 volts, a magneto machine which I intended to work as a motor from a primary battery, or from a Planté accumulator, in order to demonstrate that the Gramme dynamo is reversible. There was also a steam-engine of my invention arranged for coke firing, and a small motor of the same type, but arranged for gas-firing ; a centrifugal pump, which was intended to feed an artificial waterfall, and numerous other exhibits. To vary the experiments, I had arranged the pump so that it could receive motion either from the Gramme magneto machine or from my steam-engine. On the 1st of June it was announced that the machinery hall would be formally opened by the Emperor on the 3rd, at 10 a.m. Nothing was then in readiness, but those who have been in similar situations know how much can be got into order in the space of forty-eight hours just before the opening of an exhibition. In every department members of the staff, with an army of workmen under their orders, were busy clearing away packing-cases and decorating the spaces allotted to the different nations. The staff visited all the exhibits in order to determine which of them should be selected for the special notice of the Emperor.

"M. Roullex Duggage, the French Commissioner, asked me to set in motion all the machinery on my stand, and on the 2nd of June I was so far ready as to get the steam-engines, the plating dynamo, and the centrifugal pump to work. I failed, however, to get the motor into action, either from the primary or from the secondary battery. This was a great disappointment, especially because it prevented my showing the reversibility of the Gramme dynamo. It puzzled me the whole of the evening and ensuing night to find a means to accomplish my object, and it was only in the morning of the 3rd of June,

a few hours before the exhibition was to be opened, that the idea struck me to work the small machine by a derived circuit from the large machine. Since I had no cable, I applied to the representative of Messrs. Manhes, of Lyons, who was kind enough to lend me a small quantity; and when I saw that the magneto machine when coupled to the plating dynamo was not only set in motion, but developed so much power as to throw the water from the pump beyond the reservoir, I added more cable until the flow of water became normal. The total length of cable in circuit was then over two kilometers, and this great length gave me the idea that by means of two Gramme machines it would be possible to transmit mechanical energy over long distances."

Another version of this discovery, as given by M. Figuier, is that it was purely accidental. He says that at the Vienna Exhibition in 1873 the Gramme Company had two machines exhibited. One machine was in motion and the other was standing still. A workman noticed some cable ends trailing on the ground, and thinking they belonged to the machine which was standing, placed them in its terminals. To the surprise of everybody the machine immediately began to turn of its own accord, and then it was discovered that it was being worked by the current from the other machine.

Whichever of these two versions may be the true one, it is certain that the electric transmission of energy was known at least as early as 1873, but there is reason to believe that the idea is even older. Dr. W. Adams, in his paper "On the Evolution of the Electric Railway," [1] states that in 1840 one Henry Pinkus obtained from the

[1] Read in 1884 before the Society of Civil Engineers, America.

United States Patent Office provisional protection for his invention of an electric railway. The power was to be obtained from an electric motor—placed on the car—and set in motion by the current obtained from huge batteries. Since the latter were supposed to be buried in the ground the current must have been led to the car over some distance, and Dr. Adams says that the principle of the transmission of the current to the car while in motion for the purpose of effecting its propulsion, was the same as that used nowadays.

Thus we see that the earliest attempts at electric transmission of energy were made in combination with the problem of electric locomotion, and the following is a brief summary of the various stages the invention has passed through, as given by Dr. Adams. For fuller particulars the reader is referred to the paper already mentioned.

The first electric motor for producing rotary motion direct—as distinguished from the earlier "electric engines," which had a reciprocating action—was that invented in 1833 by Professor Henry in America. This motor was but a toy, but shortly afterwards Davenport in America, Professor Jacobi in Russia, Davidson in Scotland, and Little in England constructed motors of considerable size. Amongst these the best-known is Jacobi's motor, as applied to the propulsion of a boat on th Neva in 1839. In this instance the motive power wa furnished by a primary battery, and the motor develope about two horse-power. In 1845 Professor Page invente a new form of electric engine based on the axial force electro-magnetism, and a few years later he proposed th use of this engine for the propulsion of railway train The idea gained public favour, and Congress actuall

placed the sum of £6,000 at the disposal of Professor Page for the purpose of practically developing the invention. In 1851 an electric locomotive was built and employed to draw a train of cars between Washington and Bladensburg, a distance of five miles. The speed obtained was 19 miles an hour, but since the current was furnished by batteries, the working expenses were so great as to preclude the possibility of commercial success. It was only after the discovery of the dynamic principle by Varley, Siemens, and Wheatstone that electric railways and, indeed, any form of electric transmission of energy, became commercially possible. The idea of generating electricity at a fixed point by dynamo-machines and conveying the current through conductors and sliding contacts to the car whilst in motion, was first put into practice by Siemens in 1879, and this system forms to the present day the basis of all electric railways operated direct from the generating dynamo.

After this short review of the history of electric locomotion it will be opportune to cast a rapid glance over the earliest examples of electric transmission between two fixed points. As was already stated, the first of these experiments dates back to 1873. These, however, were experiments only, undertaken to demonstrate the idea at the Vienna Exhibition. In 1879 we find one of the earliest practical applications of the new invention undertaken by MM. Chrétien and Felix at the sugar works in Sermaize. The manufacture of beetroot sugar can only be carried on during a small portion of the year, and for the rest of the time the machinery remains idle. It was thought advantageous to utilize the steam-engine at the works during slack time for ploughing the fields round about the factory, and if this should prove success-

ful, to extend the system to other kinds of agricultural work. A Gramme dynamo in the factory was set in motion by the steam-engine there, and the current was led by insulated cables to the field to be ploughed, a distance of about half a mile. The ploughing tackle was arranged in similar manner to that in use for steam ploughing, but instead of the two steam-engines at opposite sides of the field, trollies, each provided with two Gramme dynamos and suitable gear, were employed. Each trolly was provided with the usual cable drum, and the plough was drawn backwards and forwards across the field by a steel wire-rope coiled and uncoiled alternately on these drums. Thus it was only necessary to switch the current into one or into the other set of dynamos on the trollies to produce the to-and-fro motion of the plough. After each set of furrows was completed the trollies were advanced by an equal distance until the whole length of the field was ploughed. The forward motion of the trollies was effected by the power of the motors, suitable gear having been provided for that purpose. The speed of the plough was 55 feet a minute, and the work was done at the rate of 200 square feet a minute. This performance is about equal to that which could have been obtained with a 5 to 6 horse-power Fowler steam-tackle.

At the same works, M. Felix installed in 1878 an electric chapelet-lift for discharging the beetroot from the vessels, by which means a saving in labour of 40 per cent. was effected. A similar but larger lift has recently been erected at Soissons in France, which is capable of discharging 500 tons of beetroot in twenty hours.

The early example set by M. Felix has been largely followed in France, where a considerable number of electric cranes and hoists have been erected. To mention

only a few of the more important examples, the cannon foundry at Bourges was provided in 1882 with an electric foundry crane capable of lifting 20 tons. It is worked by a 12 horse-power Gramme motor, the current being supplied by a Gramme dynamo, situated 330 yards from the crane, and requiring 20 horse-power when the maximum load is being raised. A second crane capable of raising 40 tons is now being constructed for the same works. A 40-ton foundry crane in the works of M. Joseph Farcot, which was originally designed for hand labour, has been fitted with electric gear, and the lifting speed is from three to four times as great as was formerly the case when the crane was worked by ten men. To provide against accidents, an automatic apparatus is introduced which interrupts the current when the load exceeds 30 tons. The commercial efficiency of the system—that is, the ratio of the work done in lifting the weight to the work required to set in motion the generating dynamo—is stated by M. Fontaine to be 38 per cent.

For ventilating mines and buildings, electric transmission of energy has been largely used. Electro-motors are, indeed, specially applicable for working fans, since, on account of the high speed equally required by both, the motor can be coupled direct to the axis of the fan. An early example of this kind of work is the installation at the Blanzy mines made by M. Mathet. There a fan of 2′ 7″ diameter, and 12″ wide, is placed at the bottom of the pit, 540 yards below the surface, and is worked direct by a Gramme machine, the current being supplied by a similar machine on the surface worked by a 10 horse-power portable engine. The cost of the installation, exclusive of that of the portable engine and of the fan, was £160; and M. Mathet estimates that to do the same

work by pneumatic transmission would have cost £580, apart from the fact that, on account of the lower efficiency, a much larger portable engine would have been required.

Amongst later examples of ventilating by electricity may be mentioned the Hôtel de Ville in Paris, where 35 fans, each provided with a small electro-motor, are distributed throughout the building. The current is supplied by two Gramme dynamos, each capable of delivering 50 amperes at 110 volts pressure. Either one or both of these generators may be used. Their speed is 1,250 revolutions a minute; and that of the fan motors, which are of different size, varies from 1,450 to 1,750 revolutions a minute. The current is distributed from a central switch-board, so that all the 35 fans can be controlled from this point.

A similar installation has recently been fitted up in the Ecole Centrale in Paris, but since there the fans are coupled to the motors by means of belts, special apparatus had to be employed to give warning to the engineer in case one of the belts should come off. This is done in the following manner:—In each motor circuit there is included an electro-magnet, the armature of which can assume three positions—the one home against the core when contact is made, and the normal current passes; the other right off, when an alarm-bell is put into circuit; and the third midway between these extreme positions when no current passes. The armature is held in the middle position by a catch. A spring tends to draw the armature away from the core, but with the normal current the electro-magnet is sufficiently strong to keep the armature on. Should, however, a belt fly off, then the motor will begin to race, whereby the current will be re

duced, and the attractive power of the electro-magnet will become weakened so far as to allow the spring to pull the armature off. This breaks the circuit of that particular motor, and rings the alarm-bell, thus calling the attention of the engineer to the fact that one of the ventilators is out of action.

It has been proposed by Professors Ayrton and Perry to establish electric ventilators at different points in the tunnel of the Metropolitan Railway, the current to be generated at some distant point where the nuisance of a stationary steam-engine would be far less objectionable than the fumes at present emanating from the stations and blow-holes along the line. The foul air was to be discharged from the ventilators by pipes passing through water-tanks.

Amongst other applications of electric transmission of energy, may be mentioned the pumping arrangements in use since 1883 at a mine in Thallern, in Austria. Previously to the introduction of electricity, a 6 horse-power portable engine, placed at the bottom of the pit, was employed to work a centrifugal pump delivering 66 gallons a minute through 850 yards of tubing to a height of 200 feet. Now the engine has been replaced by an electro-motor, the current being supplied by a dynamo on the surface, which gives a current of 15 amperes at a pressure of 500 volts. This represents an electrical energy of 10·2 horse-power, and allowing 80 per cent. for the commercial efficiency of the generator, the total energy expended comes to 12·8 horse-power. The energy represented in water lifted is 4 horse-power, if we do not count friction in the tube; including friction, it probably amounts to over 6 horse-power. The commercial efficiency of the installation, including the two

dynamos and the centrifugal pump, is therefore about 50 per cent.

Examples of this kind could be multiplied to any extent, as can be seen at a glance by looking through the volumes of "The Electrician" and other periodical literature for the last few years; but, strange to say, most of this class of work has been done abroad. In England it is not so much the transmission of energy between two fixed points, as the special application of electric transmission in connection with railways and tramways, which has received the greatest development. The rest of this chapter is therefore devoted to a more detailed description of some examples of electric locomotion carried out in this country; whilst the following and last chapter contains an account of the experiments of M. Marcel Deprez in France, concerning the electric transmission of energy between two fixed points.

Generally speaking, electric propulsion of carriages can be effected in one of two ways. We may either place batteries on to the car, and thus carry the source of energy along with it; or we may employ a fixed source of energy, and transmit the current to the car whilst in motion by means of a conductor and sliding contact.

For the sake of brevity we shall call the former the *battery system*, and the latter the *conductor system*. As regards their respective merits, it will be evident that the conductor system has the advantage of a more direct action, since only two conversions are required between the energy developed by the prime mover, and that actually used in propelling the car. In the battery system the energy of the prime mover must first be converted into electrical, then into chemical, energy, which is stored in the battery, and finally it must be recon-

verted in the motor into mechanical energy. The interposition of the battery between dynamo and motor must necessarily reduce the efficiency of the whole system, because we can never recover from the battery all the energy which has been put in. The extra weight which has to be carried is also a disadvantage. On the other hand, the loss of electric pressure occasioned by the resistance of the conductor may become very considerable, and the corresponding loss of energy may even exceed the energy which would be wasted in the battery. Thus the average resistance of the conductor at the Portrush Railway is 1 ohm, and when five cars are running distributed all over the line, requiring a total current of 200 amperes at 250 volts pressure, the loss of energy amounts to 37 horse-power. The power actually required for five cars is 68 horse-power, and therefore the efficiency of the conductor, even if its insulation be perfect, is $\frac{68}{68 + 37}$ $=$ 65 per cent. If we add to this the loss due to the imperfect insulation of the line, which is dependent on the state of the weather, we find that in this case the conductor system is, after all, not more economical than would have been the battery system. The Portrush line is, however, an exceptional case, as the resistance of the conductor is rather great. In the Blackpool Electric Tramway the resistance of the conductor is only half an ohm, and the loss of pressure with six cars running—on the supposition that each requires an average of 18 amperes—would be about 30 volts out of 200. In this case 15 per cent. of the energy is lost in the conductor. If this line were to be worked on the battery system the loss would probably be 10 per cent. greater.

But there is another consideration besides efficiency

which must be taken into account when deciding between the two systems. In some cases the application of a fixed conductor along the line and above ground is inadmissible on account of the other traffic which may pass over the road. Such a conductor would not only interfere with all other traffic, but being always charged, and being of necessity unprotected by an insulating covering, so as to allow for the sliding contact, it would be a constant source of danger in our crowded streets. Mr. Holroyd Smith has overcome the difficulty by placing the conductor underground, and a description of this arrangement will be given presently. Where batteries are used, each car is perfectly independent from all the other cars, and this is a great advantage in working over a complicated net of tramroads. After this rapid comparison between the two systems, we may sum up by saying that the conductor system is better for lines running across country, where an overhead conductor and high electric pressure can be used without difficulty, and the battery system is better for tramways within the crowded streets of a town.

According to the nature of the conductor, the electric railways can be further classified as follows:—

1. The rails are used as conductors, one conveying the outflowing and the other the returning current. In this case the rails must be insulated from the ground, and at the joints special connecting pieces must be used. The car wheels are insulated from their axles. An example of this kind is the short railway erected by Mr. Magnus Volk on the beach at Brighton, and the line, Berlin-Lichterfelde.

2. A separate conductor is used for the outflowing, and both rails are used for the returning current. The rails

need not be insulated from the ground, but special connecting pieces must be used at the joints to insure good conductivity. The conductor may be above ground or under ground. Examples of this kind are the railways at Portrush, Newry, and Blackpool.

3. Separate conductors are used for the outflowing and returning current. These are carried overhead on poles, and consist either of slotted copper tubes on surface railways, or of angle iron on underground railways in mines. Examples of this kind are the railways at Mödling, Berlin, Frankfurt, Zankerode mine, and others.

4. Separate conductors are used for the outflowing and returning current. These are attached to poles, and so arranged as to form one single line, along which suspended trucks run. The only example of this kind is the Telpher line at Glynde.

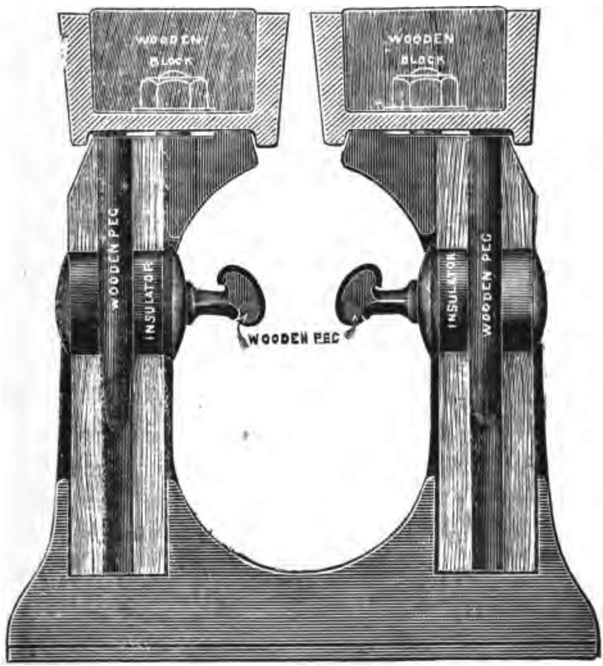
The Bessbrook and Newry Electric Railway was opened for traffic in September, 1885. It is three miles in length, and was erected to facilitate the traffic between these two towns, which amounts to about 28,000 tons annually. The generating station is placed at about the middle of the line at Millvale, where ample water-power is available. A turbine capable of working up to 65 horse-power is used to drive two Edison-Hopkinson dynamos (see description on page 241), one of these being sufficient to work the traffic, the other being held in reserve. The pressure employed is 250 volts, and the current is conveyed along a channel iron conductor laid at the same level as the rails, and supported on wooden blocks, which are attached to the cross sleepers in the centre of the track. In a front compartment of each of the two passenger cars at present in use there is an Edison-Hopkinson dynamo acting as motor, and there is

a collector with contact sliding on the centre rail, both in front and rear of the car, in order to span the breaks at farm crossings and sidings, where the current is continued by means of an underground cable. At one point the line touches the public road, and since there the conductor on the surface would be objectionable, it is interrupted for a distance of 50 yards, and the gap is spanned by two overhead wires, supported on poles 15 feet from the ground, and a collector with sliding contact is fixed to the roof of the cars for the purpose of bringing the current to the motor whilst the car is on this part of the line. The passenger car, which performs at the same time the function of an electric locomotive, weighs 8 tons, and on the level attains a speed of 15 miles an hour. It is capable of accommodating 34 passengers, and of hauling at the same time a train of loaded waggons up an incline of 1 in 85, at a speed of 7 miles an hour. The gross weight of the whole train, including locomotive and passengers, is 26 tons, and the motor develops about 25 horse-power. The steepest gradient is 1 in 50, and the sharpest curve has 150 feet radius, but at the two termini there is a pear-shaped loop with a minimum radius of 56 feet 6 inches. This arrangement obviates the difficulty of having to turn the cars on a turn-table at the end of each journey. The cars are 35 feet long, and run on double bogies, having a gauge of 3 feet, and the ordinary flanged wheels. The goods waggons have flangeless wheels, 3 feet $4\frac{1}{4}$ inches gauge, and run on two flat rails placed outside of the car rails, and $\frac{3}{4}$ inch below them. The car rails form thus a guide for the wheels of the goods waggons, and the latter can by reason of their broad flangeless wheels be at either terminus drawn off the track, and over the ordinary country roads. In the

first four months after the opening of the line, a total of 25,000 passengers and 1,600 tons of goods was carried, and the total mileage was 5,200.

In the *Blackpool Electric Tramway*, which is two miles long, the conductor is placed under ground and consists of

Fig. 110.



HOLROYD SMITH UNDERGROUND CONDUCTOR.

two semicircular channels of copper (Fig. 110), supported by, but insulated from cast-iron chairs. The conductor is split up into two parts in order that any dirt or other foreign matter which might fall through the slot in the roadway should also fall through the space between the two

halves of the conductor instead of lodging on it, as would be the case if a single conductor were placed directly under the slot. The collector consists of a steel frame narrow enough to pass through the slot and of contacts sliding along the underground conductor. The contacts are insulated from the steel frame, and are in electrical communication with a clip terminal on the car by means of an insulated cable. Light leather straps serve to draw the collector along in the slot. Should an obstruction occur in the slot or in the conductor of so serious a nature that it cannot be brushed away by the passage of the collector, the latter is arrested and the leather straps break. The strain next comes on to the insulated cable, which is thereby drawn out of the clip terminal, and thus the current is interrupted and the car comes to rest. In this manner the attention of the driver is called to the obstruction, which then can be removed by hand. From the terminal at the under-side of the car the current is led through a variable resistance and a reversing switch to the motor, and returns through the wheels to the rails, and along them back to the generating station. At first the motors were shunt-wound, so as to avoid racing when the car was lightly loaded and running on a level part of the line, or heavily loaded and running down an incline. It has been explained on page 133 that the speed of a shunt motor, when running light, can never exceed a certain limit, whereas a series motor may, under the same condition, assume a dangerously high speed. On purely theoretical grounds shunt motors are, therefore, more suitable for tramway work. But a serious practical difficulty was soon encountered. It arose from the uncertainty of electrical contact between the wheels and the rails. When a current of electricity has to pass through

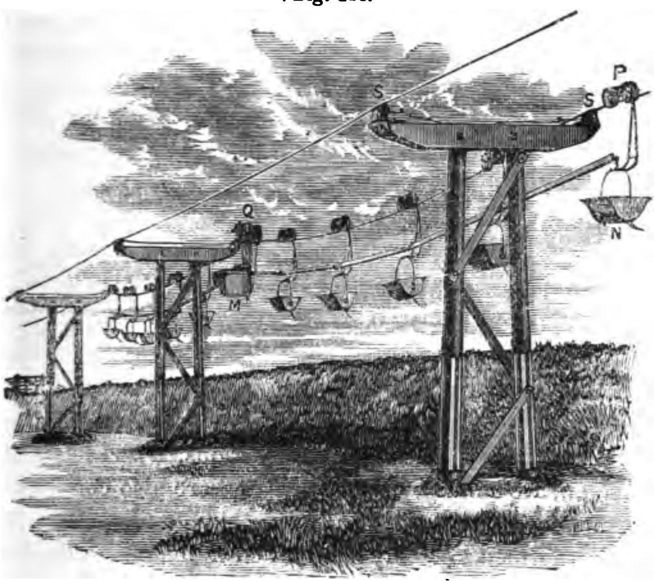
two pieces of metal in contact, the first condition is that the surfaces should be clean, and that is precisely the condition which cannot always be fulfilled in a tramway exposed to the weather, and overrun by other traffic. It would thus occasionally happen that the current was interrupted for a very short time, perhaps only a fraction of a second, but the interval was sufficient to cause the field of the motor to lose its magnetism. The consequence of this was, that when contact was restored and the current began again to flow, the armature was not able to offer any counter-electro-motive force, and an abnormal rush of current took place before the field magnets had had time to again become excited. It will be noticed that the injurious effect here described will be the greater the lower the resistance of the armature—that is to say, the more efficient the motor, the more will it suffer from an occasional interruption of current. Since it was impossible to absolutely avoid these interruptions, the use of shunt motors was discontinued, and series motors were substituted. In a series motor the intensity of the field and, therefore, the counter-electro-motive force of the armature are at once restored when the current begins to flow, and no abnormal rush of current can take place. To prevent racing when lightly loaded, variable resistances placed below the platform at either end of the car have to be used. These resistances are also employed for regulating the speed when the motor is doing a fair amount of work. The use of artificial resistances—in this case a necessary adjunct of the system—entails, of course, some waste of energy, and in this respect Mr. Reckenzaun's method of varying the power by a combination of motors is preferable. The motors—one to each of the six cars now in use—are 6 horse-power nominal, but may

for a short time be worked up to 10 horse-power, the speed being 1,000 revolutions a minute. Each motor weighs 9 cwt. It is worked at an average speed of 800 revolutions a minute, and requires an average current of 18 amperes at 200 volts pressure, or about 5 electrical horse-power, equal to 4 brake horse-power, to propel a car with 45 passengers on a level road. The direction of motion is reversed electrically by reversing the direction of the current through the armature, but not through the field magnets. In doing this the brushes are not shifted, and the diameter of commutation remains always at right angles to the magnetic axis of the field. The brushes consist of small solid blocks of copper, pressed by springs very tightly against the commutator. All screws are of steel, and provided with lock-nuts to stand the vibration of the car without becoming loose. The armatures are 10 in. in diameter, and wound with a single layer of 63 mils wire, insulated with pure silk. The generators, of which there are two, placed in a generating station at about the middle of the line, are of the type described on page 262 and illustrated in Fig. 95. Each of these dynamos weighs 4 tons, and is capable of delivering a current of 180 amperes at 300 volts pressure, when worked at a speed of 500 revolutions a minute. But since it was found that a pressure of 200 volts is sufficient to work the present traffic, the speed has been reduced to 350 revolutions a minute. The armature is 16 inches in diameter, and the field magnets, which are of the four-pole type, are separately excited by small dynamos (illustrated in Fig. 93), for the purpose of being able conveniently to alter the electro-motive force within certain limits, according to the requirements of the service.

The *Telpher Line* at Glynde is an electric railway

about a mile long, acting automatically, without assistance of guard or driver, and intended for the conveyance of a continuous stream of light vehicles, suspended from and rolling on a single line of rails, which at the same time form the electric conductors. In the illustration (Fig. 111), *M* is the telpher locomotive, consisting of an electro-motor, chain gear, and driving wheels with india-

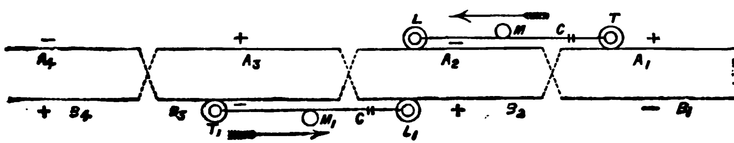
Fig. 111.



rubber treads, and also provided with two governors. One of these breaks the current when the speed attains a certain limit, and the other puts a brake on when the speed should, on a downward gradient, be still further increased. On either side of the locomotive there are placed 5 skeps, each weighing 101 lbs., and capable of carrying 250 to 300 lbs. of clay, and these skeps are kept

the right distance apart by connecting rods. The total length of the train, consisting in all of 11 vehicles, is exactly equal to the distance between two poles, and since the sections of the rail attached to the poles form alternately the out-and-home conductor, it follows that the first and last skep are at all times in contact with rails of opposite polarity. The current is collected at the two ends of the train, and conveyed along wires (not shown in the illustration) to the middle, where it works the motor, *M*. The arrangement of the circuit is shown diagrammatically in Fig. 112, where *D* is the generating dynamo, and L, T, L_1, T_1, two trains, one up and the other down the line. The sections, A_1, B_2, A_3, B_4, A_5, and so on, are

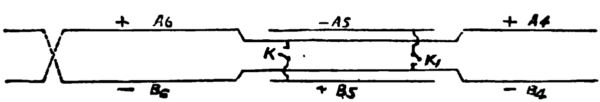
Fig. 112.



connected together by cross-connections shown in dotted lines, and are also connected with the positive terminal of the dynamo, whilst the alternate sections, B_1, A_2, B_3, A_4, and so on, are similarly connected, and are also connected with the negative terminal of the dynamo. The conductor is formed of steel rods, $\frac{3}{4}$ inch in diameter, 66 feet long between the poles, and placed 8 feet apart. The motor is regulated to run at a speed of 1,600 to 1,700 revolutions a minute, the speed of the train being 4 to 5 miles an hour. One train running backwards and forwards will deliver 150 tons of clay per week, but as many as 20 trains can be run on the double line at the same time. To avoid in this case the risk of collision, the late Professor Fleming Jenkins, in conjunction with Pro-

fessors Ayrton and Perry, invented an automatic electrical block system, which is shown diagrammatically in Fig. 113. At certain parts of the line the regular cross-over system is modified by inserting idle sections, A_5, B_5, through which the driving current is only transmitted if the switches, K, K_1, are closed. If the switch, K_1, is open, a train arriving on A_5 will stop for lack of current, and similarly, if K is open, a train arriving on B_5 will stop for lack of current. On closing the switches, the trains will start again. These switches are worked, like the contact of an ordinary relay, by a small signal current sent back by a separate circuit, and operated automatically by the preceding train. One signal opens the switch, thus blocking the line ; the next

Fig. 113.



signal closes the switch, thus again restoring communication, and allowing the following train to come on.

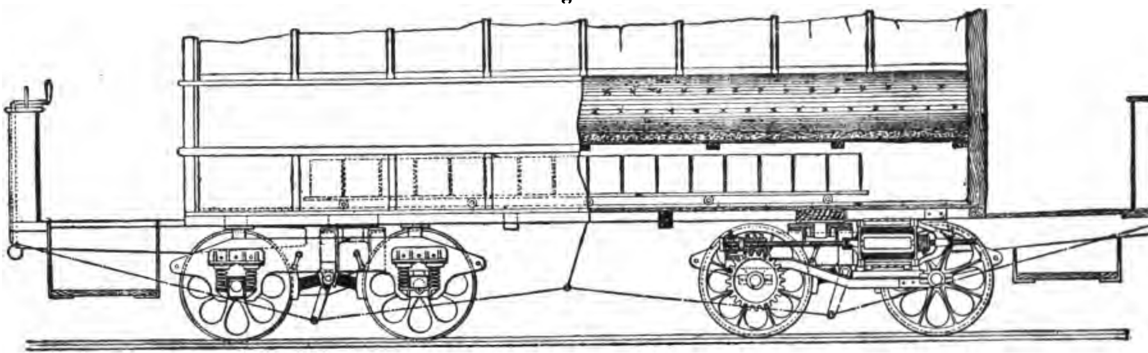
Amongst the Electric Railways worked on the battery system the most successful up to the present time is *Reckenzaun's Electric Tramcar.* Very soon after the invention of the secondary battery attempts were made both in France and in this country to utilize its capacity to store energy for the propulsion of vehicles. These early attempts, however, failed, for two reasons. In the first place, the earlier forms of accumulators were very heavy in comparison to the amount of energy which could be obtained from them, thus necessitating the carrying of an enormous dead weight, which left very little margin for the paying load. They were also unreliable, gave

but a poor efficiency, and were in many points mechanically defective. In the second place, the gear employed to reduce the high speed of the motor to the comparatively slow speed of the car-wheels was uncertain in its action, and liable to derangements. At first belt-gear was tried, but that failed when used on common roads, as might be expected of belts which have to work wet and dry, and always in a more or less muddy condition. Mr. Magnus Volk, of Brighton, has adopted belt gear in his little electric railway laid along the beach in Brighton and is quite satisfied with it. He employs leather link belts in duplicate, and each belt can be tightened by a pulley supported on a lever which is under the control of the driver. Ordinary leather belts were tried at first, but were found quite unsuitable, even on this line, which is exceptionally clean. There is no experience how leather link belts will stand on a dirty road where ordinary belts fail. Next spur-gear and bevil-gear were tried. If the distances and relative positions between the centres of the geared wheels could be kept rigidly constant, such gear would probably answer very well; but in a tramcar there is of necessity a certain amount of play between the axle-boxes and the body of the car, and the height of the car-frame above the centre of the axle is variable. There is about an inch difference when the car is loaded and when it is empty; and along our ordinary tramroads, the vertical oscillation of the car may considerably increase this difference. It is difficult to arrange spur-gear to be sufficiently flexible to accommodate itself to these changes. Chain-gear is better adapted for the purpose, and has met with a fair amount of success in Brussels and Antwerp. It is also used on many English lines.

Mr. Reckenzaun employs worm-gearing, as will be

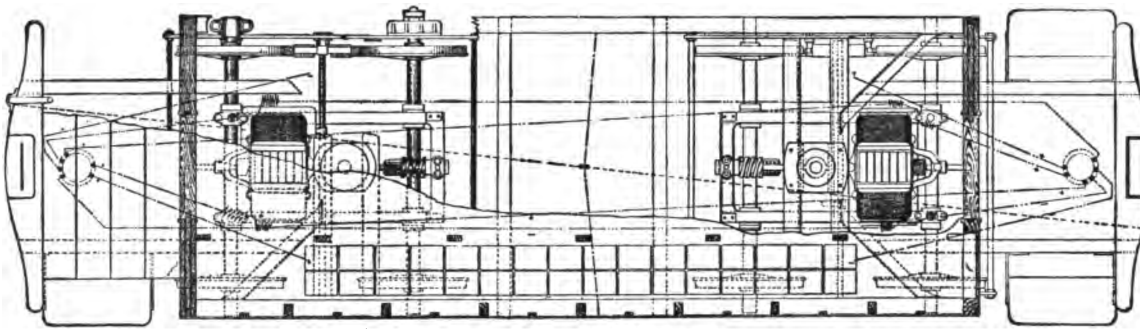
seen from Figs. 114 and 115, which represent his electric tramcar in elevation and plan. Two motors are used, each supported on, and forming part of a four-wheel bogie, which is in itself an electric locomotive, and quite independent of the body of the car. The weight of the latter is thus distributed over eight wheels, rendering it possible to run the electric car, notwithstanding its increased weight, over the ordinary tramroads. The batteries are placed on trays under the seats, and, when exhausted, can be withdrawn and replaced by a set newly charged in about the same time as it takes to change a pair of horses. To facilitate the operation, rollers are provided on which the trays run, and the latter are hauled in and out by means of a winch mounted on the trolly which brings the batteries up to the car. The object of using two motors to each car is partly to distribute the driving power to two axles without the necessity of rigid mechanical connections—which, in the case of bogie cars intended for roads where there are sharp curves would be very difficult to arrange—and partly to obtain variation in speed without the wasteful device of introducing idle resistance into the electric circuit. It will be readily seen that by coupling the motors in series the electro-motive force available for each motor will be half the total electro-motive force of the battery, whereas if we employ only one motor, or if we place both motors into parallel connection, the total electro-motive force will be available for each motor, and consequently the speed will be about double what it was in the former case. A compound switch is provided which enables the driver to make these variations in the coupling of the motors (viz., two in series, one only or two parallel) by means of a single handle. By means of another handle the direction of

Fig. 114.



RECKENZAUN'S ELECTRIC TRAMCAR.

Fig. 115.



RECKENZAUN'S ELECTRIC TRAMCAR.

motion is reversed. The car is provided, in addition to the usual hand-brake, with a very powerful magnetic brake, and with an automatic arrangement which puts this brake on if the speed exceeds a certain limit.

A car built on this principle has lately[1] been supplied to the Berlin Tramway Company, and formed the subject of an interesting paper by Herr Zacharias, read in January, 1886, before the Elektrotechnischer Verein,[2] in Berlin, to which the reader is referred for full particulars. Each motor weighs 420 lbs., or, both together, inclusive of the gear, about half a ton. The accumulators, with their trays and accessories, weigh $1\frac{1}{4}$ ton. They have to be changed every two to four hours. The total weights are as follow:—

Car, with motors, gear, and accumulators .	3·75 tons.
46 passengers, conductor and guard . .	2·25 tons.
Total . . .	6·00 tons.

The tractive force required on a level average road is 30 lbs. per ton, and at a speed of seven miles an hour this represents about $3\frac{1}{3}$ horse-power work done.

Herr Zacharias makes the following comparative estimate as regards the cost of horse traction and electric traction. He assumes that each car is actually in use from five a.m. until one a.m.—that is, for a period of twenty hours per day—and that it requires a change of horses every four hours. This gives five pairs of horses per day per car.

A line worked by sixty cars would, therefore, require 600 horses actually in service, and say ten per cent. more in reserve, or 660 horses in all.

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[1] December, 1885. [2] "Elektrotechnische Zeitschrift," Jan. 86.

To work the same line on the battery system would require steam power up to 750 horse-power, and a proportionate amount of electrical plant as given below. The capital outlay becomes—

I. For Horse Traction :—	
Horses	£28,512
Harness and other gear	2,750
Total	£31,262
II. For Electric Traction :—	
Steam-engines	£7,500
Boilers	4,000
Dynamos	2,800
140 sets of batteries	12,600
Cables and electric fittings	1,100
Motors and gear	6,000
Total	£34,000

Thus the first capital outlay is for electric traction only slightly greater than for horse traction, and if we consider that the buildings necessary to accommodate steam and dynamo machinery of a total power of 750 horse-power are not so extensive, and do not cover as much land as the buildings required to accommodate 660 horses, the balance in the first outlay may probably be in favour of electric traction. The working expenses are certainly much lower for electric traction. Herr Zacharias estimates as follows :—

I. Working Expenses with Horse Traction:—

Depreciation per horse per day .	0·4840	shillings.
Fodder „ „ .	1·5720	„
Shoeing and attendance, per horse per day	0·1613	„
Total . .	2·2173	„

Total for 660 horses and 365 days . .	£26,707
Renewal and repair of harness . .	723
Total	£27,430

II. Working Expenses with Electric Traction:—

Annual expenditure of energy, 6,570,000 horse-power hours.

Coal	£6,570
Depreciation of batteries, 20% . . .	2,520
Depreciation of motors, 20% . . .	1,200
Depreciation of boilers, steam-engines, and dynamos, 10%	1,430
Repairs, oil, acid, wages	1,180
	£12,900

According to these estimates the annual working expenses of electric traction on the Reckenzaun system would only be about half as great as with horse traction.

CHAPTER XII.

M. Marcel Deprez's Experiments—Palais de l'Industrie in 1881—Munich in 1882—Paris, Gare du Nord, in 1883—Grenoble-Vizille, in 1883—Paris-Creil, in 1885—The Generator—The Motors—General Arrangement—Regulation of Motors—Starting of Motors—Stopping of Motors—Automatic Safety Appliances.

M. Marcel Deprez is one of the earliest pioneers in the electric transmission of energy. It has already been stated in the introductory chapter that although the invention of electric transmission is not due to him, his is the merit of having first attempted long-distance transmission on a practical scale. Ever since M. Hippolyte Fontaine exhibited an example of electric transmission of energy at the Vienna International Exhibition in 1873, scientific men and practical engineers have realized that the success of the system, when applied to long distances, depends simply on the possibility to work with high electro-motive forces. If it be possible to construct generators and motors suitable for a pressure of several thousands of volts, and if the insulation of the line can at that pressure be maintained perfect, then the question is solved, and we shall be able to transmit economically and with certainty a considerable amount of energy over long distances.

Whilst most electricians who investigated the subject rested content with a solution on paper only, M. Marcel Deprez had the courage to carry his investigations into

actual practice. It cannot be denied that his first experiments were, on the whole, failures, and even the latest example of transmission, that between Paris and Creil, is not altogether a success: but they are, nevertheless, very instructive, and show a gradual improvement, as will be seen from the following short history, arranged according to the date of these experiments.

1881. *Palais de l'Industrie at the Paris Electrical Exhibition.*

The generator was a Gramme dynamo, the field magnets of which were wound with two distinct circuits, one carrying a constant current from a separate exciting dynamo, also of the Gramme type, and the other being in series with the external circuit. This generator was, probably, the first compound machine made since that of Varley, though not compounded in the same way as Varley's machine, and not as we now understand the term. The current was distributed between various motors placed at different points in the building, all the motors being in parallel connection, and each motor could be started and stopped independently of the others. The motive power was furnished by a 4 horse-power gas-engine. No trials as regards efficiency were made, and the chief interest of the exhibit lay in this, that it was shown that the transmission and distribution of mechanical energy by means of electricity was not only possible on paper but an actual fact.

On this occasion, in a paper read before the Congrès International des Electriciens, M. Marcel Deprez gave it as his opinion that it would be possible to transmit 10 horse-power over an ordinary telegraph wire to a distance of 30 miles, the energy expended at the generating station

being 16 horse-power. To test the correctness of this statement, the committee of the succeeding electrical exhibition in Munich invited him to show a system of transmission in actual work, and placed a telegraph line at his disposal. In consequence of this offer were undertaken the experiments of 1882 *between Munich and Miesbach.*

The distance between generator and motor was 57 kilometers, or about 35 miles, and since considerations for the public safety excluded the use of an earth return, the current had to traverse about 70 miles of telegraph wire in the out-and-home circuit. The resistance of the line was 950 ohms. It was intended to submit the installation to exhaustive tests, which were to be made by the jury, but a series of accidents which happened to the machinery greatly interfered with any systematic investigation. Finally, one of the brushes of the motor became loose and fell out, thus suddenly interrupting the current. The effect of this accident was to completely destroy the insulation of the machines, and no more tests could be taken. The few readings which were obtained previous to this mishap will be found on pages 71 and 72 of the official report of the Exhibition Committee, published in Munich in 1883, and from these figures it appears that the commercial efficiency of the system was about 25 per cent. The power applied at Miesbach varied between 1·04 horse-power and 1·14 horse-power, and that recovered at Munich varied between 0·224 horse-power, and 0·259 horse-power. The average current was a little over half an ampere, and the pressure at the terminals of the generator was about 1,300 volts. The speed of the generator was 1,600 revolutions a minute, and that of the motor averaged about 700 revolutions a minute.

1883. *Experiments at the Gare du Nord in Paris.*

For these experiments a special generator was constructed, whilst the motor was a D Gramme machine, wound with fine wire, so as to be suitable for a high pressure. The generator was provided with two armatures, mounted one behind the other upon the same spindle, which revolved between the poles of two horizontal horse-shoe magnets. The yokes of these magnets were bolted to a cast-iron base-plate, and the cores were cylindrical and provided with polar extensions. The centre line of each pair of magnets was at right angles to the spindle.

The generator and the motor were both placed in the same room, and their terminals were connected by two wires—one, a stout and short copper wire of practically no resistance, and the other a telegraph wire of galvanized iron, 160 mils diameter, and about $10\frac{1}{2}$ miles long. This length of wire was obtained by carrying it out to Bourget and back again in a loop, the total resistance of the line being 160 ohms. It will be seen that this arrangement, although very convenient for taking simultaneous measurements at the dynamo and at the motor, is not exactly a representation of what is met with in actual practice. It has already been stated that one of the difficulties to be overcome in long-distance transmission is the proper insulation of the line. This difficulty is of course greatest where the dynamo and motor are placed at the two ends of the line, for then the pressure between the out-and-home circuit is that actually existing between the terminals of the generator. If, on the other hand, the machines are placed side by side, and connected by a short stout wire, which can easily be insulated, then the

pressure between the outgoing and returning loop of the telegraph wire is only that resulting from the resistance of that wire and the current flowing, and therefore much smaller than in the previous case. It should also be noticed that a short circuit between the two loops of the telegraph wire, instead of being fatal to the system, would only have the effect of reducing the resistance of the line, and thus make the efficiency appear higher than it really is. To exclude the possibility of such an error, the difference of potential between the terminals of the loop of telegraph wire was always taken simultaneously with the current, and by dividing the former by the latter, the actual resistance of the line at the time of each experiment could be ascertained. The figures obtained were, with the exception of the last, fairly in accordance with the resistance of 160 ohms measured on the Wheatstone bridge, as will be seen from the table below. The measurements were made by a committee appointed by the Académie des Sciences, and published in their report at length. The table here appended is a short abstract of this report, which will be found reprinted at full length in "La Lumière Electrique," t. xviii., No. 45.

Experiments at the Gare du Nord in 1883.

Revolutions per minute.		Pressure at Terminals in volts.		Current Amperes.	Actual Resistance of Line.	Horse-power.		Commercial efficiency per cent.
Generator.	Motor.	Generator.	Motor.			Expended.	Recovered.	
378	104	722	321	2·39	167	3·838	0·578	15·1
370	88	745	355	2·52	155	3·854	0·489	12·7
850	602	—	—	—	—	9·771	3·344	34·2
923	709	2,086	1,685	2·52	159	10·556	3·939	37·2
850	643	1,937	1,479	2·57	179	9·514	3·572	37·5
1,024	799	2,338	1,994	2·50	138	12·267	4·439	36·2

It will be seen from this table that in point of commercial efficiency a marked advance had been made over the Munich experiments.

1883. *Experiments at Grenoble and Vizille.*

The town of Grenoble, situated in a mountainous district where water-power is abundant, but not easily accessible, seemed to offer a very promising field for electric transmission of energy, and the next experiments were carried out between Grenoble and Vizille, over a distance of 8½ miles. The generator was installed at Vizille, and driven by a turbine, whilst the motor was placed in the centre of the town of Grenoble. The arrangements adopted at the generating station permitted the power of the turbine to be sent either into the generator or into a brake dynamometer, where it could be measured. By keeping the working conditions, viz., head of water, opening of the turbine gates, and speed, the same in both cases, the power measured by the brake can be considered as equal to that supplied to the generator, equality of speed being obtained by properly loading the brake. The power received at Grenoble was also measured by a brake. In this installation the objections raised above with regard to the loop in one of the circuits cannot be urged, as any imperfection in the insulation of the line must have manifested itself in a falling off in the energy received, and, therefore, in the efficiency of the whole system. The circuit consisted of two wires of silicon bronze 80 mils diameter, the total resistance being 167 ohms.

The trials were made, as before, by a commission appointed for the purpose, and they have been published in "La Lumière Electrique," t. xviii., No. 45; but their

practical value is somewhat impaired by the fact that, from the power supplied to the generator, a certain deduction had been made to allow for the friction in the gearing. Now, from a commercial point of view, this is not permissible, for some kind of gearing is necessary to get up the high speed which makes the system electrically efficient, and the loss of energy in the gear is a necessary factor in the generating station, and has to be paid for in some way or other. The figures given below are, therefore, somewhat higher than the actual commercial efficiency.

Experiments between Vizille and Grenoble in 1883.

Revolutions per minute.		Electro-motive Force in Armature of		Current Amperes.	Horse-power.		Efficiency per cent.
Generator.	Motor.	Generator.	Motor.		Delivered to Generator.	Recovered from Motor.	
724	604	1,788	1,066	2·25	5·79	2·75	47·5
810	641	2,163	1,332	2·59	7·25	3·65	50·3
915	684	2,480	1,613	2·70	8·03	4·67	58·1
950	646	2,736	1,709	3·20	9·97	5·88	58·9
1,000	638	2,960	1,846	3·47	15·47	6·53	42·2
1,050	734	2,992	1,981	3·15	12·33	6·68	54·1
1,140	875	3,146	2,231	2·85	11·18	6·97	62·3

The highest electro-motive force developed in the armature of the generator was over 3,000 volts, as will be seen from the table, that at the terminals of the machine being about 2,960 volts. The maximum energy transmitted was close upon 7 horse-power.

1885. *Experiments between Paris and Creil.*

After the above brief historical sketch of M. Marcel Deprez's previous experiments, the trial which has just

been concluded on a line between Paris and Creil deserves a somewhat more detailed description. For a full account, the reader is referred to "La Lumière Electrique," t. xviii., Nos. 44, 46, 47, 48.

The Generator.—The dynamo which generates the current is situated at Creil, and receives motion by means of a counter-shaft from two locomotive engines which were specially adapted for that purpose. The wheels have been removed, and the frame rests on special supports. Two large pulleys have been fitted to each locomotive, one on either end of the crank shaft, so that the driving-power is transmitted to the counter-shaft by four wide leather belts. From there it flows through four other belts to the generator, which is provided at either end with a double set of pulleys. The generator is of the type shown in Figs. 116 and 117, and was specially constructed for the purpose. It has two armatures, each surrounded by eight magnet cores with segmental pole pieces, the four above the horizontal centre line forming one pole and the four below that line forming the other pole. Each armature revolves, therefore, in a two-pole field, but each pole is produced by four distinct magnets. After what has been said in Chapter IV. about the resistance of the magnetic circuit, and the amount of wire necessary to excite single and multiple magnets, it will be evident that M. Marcel Deprez's arrangement of field magnets requires more copper and more electrical exciting energy than the ordinary single horse-shoe field, and is, therefore, the reverse of an improvement. In our good modern English dynamos the energy required to produce the magnetic field seldom exceeds 5 per cent. of the total electrical energy of the armature, whereas in the dynamo just described, about 18 per cent. of the total energy is required

Fig. 116.

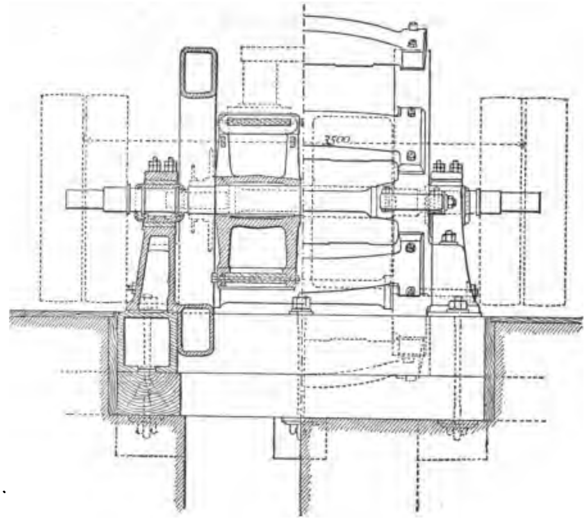
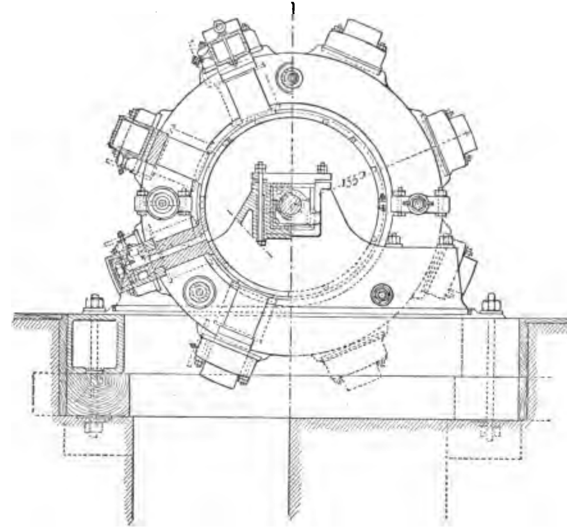


Fig. 117.



MARCEL DEPREZ DYNAMO.

to maintain the magnetism of the field, as will be seen from the table below. The figures were communicated by M. Marcel Deprez to the French Academy on the 26th October, 1885, and refer to a preliminary experiment made at Creil, the generator and motor being placed side by side, and connected by a loop 70 miles long, in the same manner as in the experiments at the Gare du Nord. The looped conductor was a copper cable, equal in section to a solid wire of 197 mils diameter.

Preliminary Experiments, Creil—La Chapelle—Creil.

Resistances { Generator, two armatures 33 ohms. Motor, two armatures 36 ohms. Line .... 100 ohms.	First Experiment.		Second Experiment.	
	Generator.	Motor.	Generator.	Motor.
Revolutions per minute . . .	190	248	170	277
Internal Electro-motive Force .	5,469	4,242	5,717	4,441
Current.	7·21	7·21	7·20	7·20
Horse-power required to maintain the Magnetic Field . .	9·20	3·75	10·30	3·80
Electrical Horse-power in Armature	53·59	41·44	55·90	43·40
Mechanical Horse-power . . .	62·10	35·80	61·00	40·00
Electrical Efficiency, per cent. .	77		78	
Commercial[1] Efficiency, per cent.	47·7		53·4	

The mechanical horse-power delivered to the armature of the generator was measured by a White's transmission

[1] From the note presented to the Academy it is not quite clear how the efficiency was calculated. If we include the energy required to maintain the magnetic field in the calculation, the result is as follows:—

$$\text{First experiment,} \quad \frac{35{\cdot}80 - 3{\cdot}75}{62{\cdot}10 + 9{\cdot}20} = 45 \text{ per cent.}$$

$$\text{Second experiment,} \quad \frac{40{\cdot}00 - 3{\cdot}80}{61{\cdot}00 + 10{\cdot}30} = 50{\cdot}7 \quad ,,$$

dynamometer; that given out by the armature of the motor was measured by a Prony brake.

The generator which will ultimately be employed at Creil is a somewhat larger machine than that which served for the above preliminary experiments. A very full description of it will be found in "La Lumière Electrique," t. xviii., Nos. 46 and 47. Each of the sixteen magnet cores is a cylinder, 10 in. in diameter and 23 in. long, weighing 240 lbs. Each of the eight horse-shoes, consisting of two magnet cores and a cast-iron yoke, weighs 1,070 lbs. The exciting wire is 98 mils diameter, and about 35 miles of it are used for the 16 magnets, the total weight of copper being 5,700 lbs., or about $2\frac{1}{2}$ tons. To facilitate the winding, and to render the insulation more perfect, the wire is wound on separate narrow reels, 12 such reels being placed on each of the 16 cores.

The core of the armature is built up of segments of soft sheet iron, each segment forming the eleventh part of a circle. These segments are held together by eleven insulated bolts, and are supported at each end by a set of eleven gun-metal arms cast in one piece, with a central hub, by which the armature is keyed to the spindle. Each of the two armature cores has a diameter of 52 in., and a radial depth of $2\frac{3}{4}$ in.; it is 20 in. long. When wound with copper wire the external diameter of the armature is $54\frac{1}{2}$ in., and the internal diameter is 42 in. The wire is 98 mils diameter, and the total length contained on each of the two armatures is 13,000 yds., weighing, inclusive of insulation, 1,200 lbs. It is stated in the article above mentioned that this armature has, in a preliminary trial, developed an electro-motive force of 16 volts for every revolution per minute. Now the value of an armature

can be expressed by the relation which the electro-motive force bears to the total length of conductor if the armature be run at a certain fixed circumferential speed.[1] To make all armatures equally safe with regard to the action of centrifugal force, this speed ought to be the same in all cases, and the general practice in English machines of the drum or cylinder type is to allow about 3,000 ft. per minute as a safe maximum of circumferential speed. If we adopt this rule in the case of the armature just described, we find that it might safely be run at a speed of 220 revolutions, when the electro-motive force developed would be 3,520 volts, being at the rate of 1 volt for every 3·7 yards of armature conductor. It is interesting to contrast with this figure the results obtained in the usual English and American practice. In the following table are given the numbers of yards of armature conductor required by various machines, all reduced to a circumferential speed of 3,000 ft. per minute.

	Yards.
Edison-Hopkinson	·510
Manchester	·970
Crompton	·860
Elwell-Parker, 2-pole	1·470
Elwell-Parker, 4-pole	1·000
Phœnix	1·160
Goolden and Trotter	1·250
Kapp	·970
Brush, high tension machine	2·220
Thomson-Houston high tension machine	3·550
Marcel Deprez	3·700

[1] See the author's paper on "Modern Continuous Current Dynamos and their Engines," read before the Institution of Civil Engineers on the 24th of November, 1885, vol. lxxxiii., part 1.

The Motors.—The current produced by the generator just described is to be utilized at La Chapelle to work two motors of the same type as the machine illustrated in Figs. 116 and 117, the only difference being that they are somewhat smaller, and that the field is produced by six instead of eight horse-shoe magnets. The core of each armature is 34½ in. diameter, 2⅜ in. deep, and 16 in. long; it is supported on seven double arms, and wound with 6,300 yards of 98 mils wire. The total length of wire contained in the existing coils of the 12-magnet cores is 27,500 yards. The wire is insulated with two servings of silk and one of cotton, and then varnished.

Exciting Machines.—The generator as well as the two motors are separately excited, the former by a C C Gramme dynamo, and each of the latter by a C Gramme dynamo. The larger machine has two armatures 10 inches in diameter and 7½ inches long, and at a speed of 1,000 revolutions a minute it develops an electro-motive force of 210 volts. The smaller machines have each one armature only, of the same dimensions, and develop 105 volts at the speed of 1,000 revolutions a minute, the current in both cases being 25 amperes.

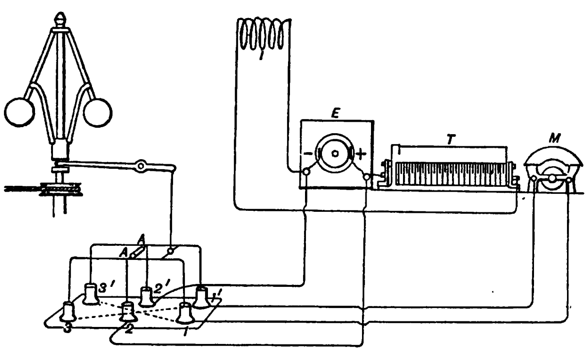
General Arrangement.—The generator has been designed for an internal electro-motive force of 7,500 volts, and a maximum current of 20 amperes.[1] It will be kept running at a constant speed, and the intensity of its field will also be kept constant by maintaining the exciting current of the C C Gramme at the same value, whatever be the output of the generator. Beyond two centrifugal governors—one to each steam-engine—no other regulat-

[1] Since the above was written trials have been made, and then it was found that the strength of current which can safely be used is much smaller.

ing apparatus is, therefore, required at the generating station. The internal resistance of the two armatures of the generator in series is 20 ohms, and the resistance of the main line is 100 ohms, measured up to the point where the two parallel circuits are joined which carry the current to the two motors. The resistance of each motor circuit, including its armatures, is 20 ohms. When in full work the pressure at the end of the mains is therefore $7,500 - 120 \times 20 = 5,100$ volts, and the counter-electro-motive force of each motor is $5,100 - 20 \times 10 = 4,900$ volts. When only one motor is at work, the current sent out from the generator is 10 amperes, and the pressure at the end of the mains is therefore $7,500 - 120 \times 10 = 6,300$ volts, the counter-electro-motive force of the motor being $6,300 - 20 \times 10 = 6,100$ volts. To maintain the speed of each motor constant and independent of the other motor, it is only necessary to be able to vary its counter-electro-motive force between 4,900 and 6,100 volts, which is done by varying the intensity of its field. This is accomplished automatically by an apparatus which works a rheostat of 20 ohms inserted into the circuit of the exciting dynamo. The general arrangement of this apparatus is shown diagrammatically in Fig. 118, where E represents the exciting dynamo, T the rheostat, M a small magneto motor, which works the rheostat by means of a current derived from the exciting dynamo, and the direction of which is controlled by the reversing switch A A, and I represents the exciting coils of the large motor. When the reversing switch stands in the position as shown in the diagram, no current passes through the armature of the magneto motor, and that remains at rest. But if the speed of the governor—which receives motion directly from the spindle of the large

motor—should rise, the balls fly out, and the contacts of the switch are dipped into the mercury-cups 1, 1 ; on the other hand, if the large motor runs below its proper speed, the balls of the governor drop, and contact is made with the mercury-cups 3, 3. A current is therefore sent through the magneto-motor in one or in the other direction, causing it to work the rheostat, so as to insert more resistance when the large motor runs below its normal speed, and to withdraw resistance when it runs above its normal speed. The rheostat is also provided with a crank

Fig. 118.



REGULATOR.

so as to be worked by hand if a rapid change of intensity of the field of the large motor be required. This is the case when it is desired to stop the motor, as will be explained presently.

The exciting dynamo receives motion from the motor, and once the machinery is started there is no difficulty in maintaining the magnetic field of the motor. But when standing the intensity of the field falls to zero ; and if in this condition the current from the line were sent through

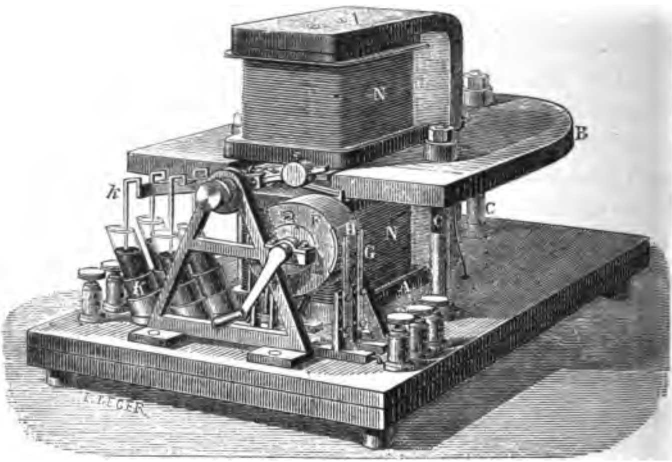
the armatures of the motor, it would fail to produce rotation, that is to say, the motor could not start. For the purpose of starting it is therefore necessary to produce the magnetic field independently of the exciting dynamo, and this is done by allowing the line current to flow at first through the exciting coils of the field magnets, so that the motor acts for the time being as an ordinary series machine. As such it starts easily, and after it has attained a certain speed, the line current is gradually withdrawn from these coils, and the current from the exciting dynamo is as gradually substituted, the whole operation being performed by the aid of a special commutator. It will be noticed that the subdivision of the exciting coils into many distinct sections greatly facilitates the transfer of each coil from one circuit to the other.

The problem how to stop the motor without first stopping the generator presents, perhaps, the greatest difficulty. In a small installation, where only a low electromotive force is employed, we would simply provide each motor with a switch and interrupt the current by the switch whenever we wanted to stop the motor. But to do that with a motor fed at a pressure of 5,000 to 6,000 volts would, in all probability, cause the destruction of the motor, and possibly endanger the safety of the person handling the switch. The danger arises from the fact that the self-induction in the motor-circuit is, on account of the great length of wire employed, enormously great. The electro-motive force of self-induction can be considered to be proportional to the square of the number of turns wound on the armature of the motor and to the current passing. Before it is safe to switch off it is therefore necessary to reduce the current very con-

siderably. This can be done in two ways. We may either insert into each motor circuit a variable resistance, and increase it until the current passing is about 1 ampere. At this moment the armature of the motor can be short-circuited on itself, and thus quickly stopped. Or we may suddenly increase the counter-electro-motive force of the motor, which will also check the current, and then switch off. The latter process is performed in the following manner: the load is taken off the motor, and at the same time the automatic regulator is switched out of circuit, the rheostat being worked by hand. It is first set so as to introduce the whole of the 20 ohms into the exciting circuit, thus reducing the strength of the magnetic field to a minimum. The immediate result of this is that the speed of the motor will increase very considerably above the normal value. The rheostat is now quickly thrown over into the position where all the resistance is withdrawn from the exciting circuit, and the current producing the magnetic field has its greatest value. In consequence of thus suddenly raising the strength of the field whilst the motor is running at an excessive speed, its counter-electro-motive force grows quickly up to the electro-motive force in the main line, and may for a short time even exceed it. At the moment when the two electro-motive forces are equal, no current passes, and the motor circuit can be interrupted without danger. As it would be difficult to hit the right moment when the circuit should be broken, the switch is not worked by hand, but by a special electro-magnetic cut out, Fig. 119. *B* is a strong steel magnet tending to keep a flat lozenge-shaped armature which can swivel about a horizontal axis, and is placed between its poles in a horizontal position. This armature is at the same time under the influence of an

electro-magnet, *N A*, which tends to draw the armature out of its horizontal position, and when sufficiently excited, will hold it in the inclined position indicated in the illustration. On the axis of the armature is placed a lever, provided at one end with contact-pins, *K*, dipping into mercury-cups, and at the other with a balance-weight by which the sensitiveness of the apparatus can be regulated within

Fig. 119.



AUTOMATIC CUT OUT.

certain limits. Two of the mercury-cups are joined in series with the line, and the other two are in series with the exciting circuit ; but to avoid the necessity of keeping the current flowing through the mercury, each pair of cups is also in connection with spring contacts controlled by the commutator, *F*. When the latter is in the position shown the apparatus is not in action. But on turning the handle of the commutator through 90° the spring contacts are broken and the currents flow through the mercury-

cups. When in action the line current flows also through the electro-magnet, *N A*, and tends to keep the armature inclined. If now the motor be allowed to race, and then its field be suddenly increased in the manner above described, there comes a moment when no current passes through the line and through the electro-magnet, *N A*. At that moment the latter loses control over the lozenge-shaped armature, which is pulled into a horizontal position by the steel magnet, *B*, and thus the contact-pins, *K*, are pulled out of the mercury-cups. In this manner both the line circuit and the exciting circuit are simultaneously interrupted.

To prevent injury to the generator from an accidental short circuit on the line, and consequent excess of current, an electro-magnetic relay is introduced which acts when the line current exceeds 20 amperes. If this should at any time be the case, the armature of the electro-magnet releases a trigger by which a heavy weight suspended by a rope from a pulley is allowed to descend. The movement thus obtained is utilized to switch into the line a large resistance, and thus prevent an excess of current.

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